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Investigation of Smooth Specimen SCC Test Procedures. Variations in Environment, Specimen Size, Stressing Frame, and Stress State

Final Report - Part II

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ALCOA

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GEORGE C. MARSHALL SPACE FLIGHT CENTER
CONTRACT NO. NAS 8-21487

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(July 1, 1969 to February 29, 1972)

Investigation of Smooth Specimen SCC Test Procedures-Variations in Environment, Specimen Size, Stressing Frame, and Stress State

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Foreword

This report was prepared by The Aluminum Company of America under Contract NAS 8-21487 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work described herein was performed between July 1, 1969 and February 29, 1972. The project was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the George C. Marshall Space Flight Center with Mr. T. S. Humphries serving as project manager. This report may not be reproduced or published in any form, in whole or in part, without prior approval of the U.S. Government.

Part I of this contract, titled Evaluation of Stress-Corrosion Cracking Susceptibility Using Fracture Mechanics Techniques[1], was conducted between July 1, 1968 and February 29, 1972, and is reported separately. The objective of Part I of the contract was an evaluation of the resistance to stress-corrosion cracking (SCC) of a group of high strength aluminum alloys and precipitation hardening stainless steels by both fracture mechanics and conventional, smooth specimen techniques; including a determination of the applicability of the data obtained by the two methods.

SUMMARY

Part II of the Marshall Space Flight Center Contract NAS 8-21487 was a study of certain variables in the conventional smooth specimen test procedure that affect the stress-corrosion cracking (SCC) performance of high strength aluminum alloys. The variables studied were:

A. Corrosiveness of the environment,

B. Specimen size and stiffness of the stressing system,

C. Interpretation of transgranular cracking, and

D. Interaction of the state of stress and specimen orientation in a product with an anisotropic grain structure.

Synopses of the scope and outcome of tests in these four areas are given below. Specific conclusions arrived at are listed in Part VII of the text.

A. Corrosiveness of the Environment

The study of the corrosiveness of the test environment was made on rolled plates of seven alloy-temper combinations using an 1/8-in. dia. tensile specimen and Alcoa's standard stressing system. The tests evaluated the 3.5% NaCl alternate immersion test (A.I.) per Federal Method 823 and four modifications aimed at reducing adverse pitting corrosion that can cause non-typical transgranular fracturing.

The corrosiveness of the Method 823 A.I. test was markedly reduced by two of the modifications, namely: addition of a copper chelating agent and use of synthetic ocean water per ASTM D-1141-52. Both of these modifications reduced the

incidence of transgranular cracking, especially for the first two months of exposure. However, there was an indication that use of synthetic ocean water also decreases the ability to detect slight susceptibility to SCC.

Although the program did not achieve a fully satisfactory method, it does point up the need for refinement of the presently accepted Method 823 A.I. test and indicates some promise in this direction.

For certain experimental 7XXX-T7 alloys, such as the one included in this program (X7375 + Zr + Ag), the A.I. test does not reproduce the same SCC tendencies manifested in atmospheric exposures. None of the modifications of the A.I. test evaluated improved this situation.

B. Specimen Size and Stiffness of the Stressing System

The study of the effect of specimen size and stiffness of the stressing system was twofold. In one phase SCC tests were made on five alloy-temper combinations in the Method 823 A.I. Both 1/8 and 1/4 inch diameter specimens were used and the 1/8 inch specimen was loaded in two sizes of stressing frames. The second phase consisted of compliance tests to determine the increase in net section stress with reduction in net section area as affected by the toughness of the alloy and type of corrosion pattern. Eight alloys were used to provide a wide range in toughness and three types of machined notches to simulate local corrosion flaws. This phase also included analysis of the effect of variation in the stiffness of the stressing system

associated with different specimens and stressing frames.

It has been well established that the probability of failure and the time to fracture of a stress corrosion test specimen depends on the magnitude of applied stress and the corrosive environment. These two factors are the primary conditions affecting initiation and propagation of SCC. The present work has shown that, for a specimen loaded in direct tension by any method other than a dead load, the probability of failure and time to fracture also can be markedly influenced by the corrosion pattern, the stressing assembly stiffness and the notch tensile strength of the alloy.

The corrosion pattern that occurs can influence the net section stress and time to fracture over the full range of effects expected in shifting from constant load to constant deformation stressing. The most adverse pattern is highly localized and non-symetrical corrosion (single edge notch), while general corrosion that effectively causes a uniform reduction in cross section is the least damaging.

The stiffness of the stressed assembly is affected by the diameter and length of the specimen and the rigidity of the stressing frame. Stiffness has only a slight effect on the probability and time of failure when highly localized corrosion occurs because the net section stress increases rapidly to the breaking strength even for an infinitely stiff assembly. Conversely, the increase in stress with uniform, general corrosion is gradual enough with the type of stressing assembly used so that the specimen can corrode completely away without actually breaking,

just as with an infinitely stiff assembly. However, intermediate corrosion patterns usually occur in A.I. tests of alloys with limited susceptibility to SCC. In such cases stiffness can have a marked effect and may be the determining factor as to whether fracture occurs.

In general, the actual SCC data obtained were in agreement with theoretical expectations. While the interaction of specimen size and stiffness could not be separated, the 1/8-inch specimen loaded in either size frame had about the same assembly stiffness and the number and times to failure were likewise similar. The 1/4 inch assembly was about 4 times as stiff and fewer failures with longer failure times occurred. Use of the 1/4 inch specimen reduced, but did not eliminate, the occurrence of non-typical transgranular cracking.

C. Interpretation of Transgranular Cracking

Service experience and prolonged atmospheric tests have shown that alloy 7075-T73 has a very high resistance to SCC. In spite of this, several of the 7075-T7351 specimens in this investigation fractured at high applied stresses after long exposure. Likewise specimens from the experimental 7XXX-T7351 alloy fractured after relatively short exposures. Fractographic and metallographic examinations of these specimens established that the cracking was transgranular and not intergranular as is characteristic of SCC in susceptible aluminum alloys. Scanning electron microscopy of the fractured faces showed these transgranular cracks had brittle characteristics different from the dimpled surface of a ductile tension fracture. Ray patterns were

observed that resemble Stage 1 fatigue failure in aluminum alloys and also the transgranular SCC in austenitic stainless steel. Additional evidence is needed to establish whether these cracks are some kind of mechanical crack or transgranular SCC. Thus far, however, it seems probable that they are corrosion assisted mechanical cracks.

D. State of Stress and Specimen Orientation

These tests were conducted on 7075-T651 plate using thin wall, hollow-core specimens and the Method 823 A.I. test. Specimens were oriented in the longitudinal, long transverse, and short transverse directions and at an angle of 45° between long transverse and short transverse. The specimens were loaded in tension, torsion and compression. The normal and shear stresses acting on various planes in these specimens were described by means of Mohr's circles.

The results show that in a product with a highly directional grain structure, the greatest tendency for SCC is caused by a combination of a normal tension stress and a shear stress acting on the plane of maximum susceptibility, which for aluminum is the short transverse plane. However, a shear stress acting alone in this plane will also cause SCC, and with torsion loading of a specimen there will always be at least a shear stress in this plane regardless of the orientation of the specimen. From a design standpoint, therefore, it is advisable to look at all sustained torsional load situations to determine whether there is a potential SCC hazard.

Tests of specimens loaded in compression confirmed that compression stress does not cause SCC and can repress the SCC tendency associated with shear stress.

I. INTRODUCTION

The laboratory test most commonly used in the United States for determining the resistance to stress-corrosion cracking (SCC) of aluminum alloys is the 3.5% NaCl alternate-immersion test. The test involves a one hour cycle, consisting of a 10 minute immersion of the specimen in the 3.5% NaCl solution followed by drying in air for 50 minutes, with the cycle continued 24 hours per day for the prescribed exposure period. Although this alternate immersion test dates back to the early 1940's, the first attempt to develop a standard procedure for use throughout the industry was in 1967. This was an outgrowth of a government sponsored test for aluminum alloy ballistic armor plate, resulting in Method 823 of Federal Test Standard 151b. More recently an ASTM committee (ASTM G01.06.02, T.G. 11) has recommended a more detailed method, stipulating additional test conditions beyond those required by Method 823 in an attempt to minimize variability resulting from testing procedure.

A disadvantage of the 3.5% NaCl alternate immersion test for use with high strength aluminum alloys, primarily copper containing alloys, is the severe pitting that develops in the test specimens. Such pitting can interfere with the initiation of SCC. Depending on the nature of the pitting corrosion, this interference can have a diminishing or augmenting effect. In cases where the pitting is very general so as to effectively cause uniform thinning of the specimen, SCC may be delayed or prevented entirely[2]. The more typical case, however, is pitting at discrete

sites causing a localized increase in the net-section stress. This may result in non-typical failures of a mixed intergranular + transgranular nature, or a purely transgranular nature; the extreme case being a mechanical failure merely as a result of reduction in cross-section(3). These non-typical failures complicate the interpretation of the accelerated stress-corrosion test results.

Recent alternate immersion tests conducted per Method 823 have shown that the high purity solution specified (reagent grade salt plus distilled water) tends to cause more localized and deeper pitting corrosion than solution made with commercial grade salt and tapwater. However, the controlled purity solution has the advantage of being readily standardized throughout the industry. This contract, therefore, was extended to study modifications of Method 823 alternate immersion intended to provide a less corrosive test medium, while maintaining the ability to detect susceptibility to SCC.

The effect of pitting on SCC performance would be expected to be a function not only of the depth and distribution of the pits but also a function of the cross-section area of the specimen and the relative stiffness of the stressing system. Hence, these variables were incorporated into the program.

The scope of the program undertaken was not intended to provide a final solution to the problem. Rather the intent was to explore certain possibilities with the hope of establishing trends or significant factors that could be the basis for further work.

In a supplementary part of the program, a limited fundamental study was undertaken to demonstrate:

a. The stress state necessary to cause SCC, and

b. The effect of combined stresses in relation to the directional grain characteristics of high strength aluminum alloys.

II. OBJECTIVE

Specific objectives of Part II of the contract were:

a. Determine the effectiveness of four variations of the alternate immersion test in providing a less corrosive medium than the 3.5% NaCl solution specified in Federal Test Standard 151b, Method 823.

b. Determine how the stress-corrosion performance is affected by an increase in (1) specimen diameter and (2) stiffness of the stressing system.

c. Demonstrate: (1) the stress state necessary to cause SCC and (2) the interaction of stress state and specimen orientation in a directional grain structure.

III. MATERIAL

The materials used in Part II of the contract were aluminum alloy plates, 2.000 to 2.625 inches thick, some of which were available as overage from Part I of the contract, fabricated by Alcoa with standard plant procedures. The various alloys and tempers used are listed in Table I with tensile properties and chemical composition. Alloys 2024 and 7075 were obtained in the T351 and T651 tempers and a portion of each was then artificially aged at Alcoa Research Laboratories (ARL) to the T851 and T7351

tempers, respectively. Because the supply of 7075 plate was limited, a second lot of 7075-T651 plate was procured for the program on state of stress.

All the compositions listed in Table I are within the limits specified by The Aluminum Association[4]. The long-transverse tensile properties of the six commercial alloys and tempers exceed the guaranteed minimum values[4].

Table I ranks the seven alloy-tempers as having "low" or "high" resistance to SCC in the short-transverse direction. This terminology is strictly a relative ranking of alloys that fail under moderate short-transverse stresses (20 ksi and less) as opposed to alloys that are resistant at stresses of 50% Y.S. or higher. A "low" ranking does not imply that an alloy is not useful, nor does a "high" rating necessarily imply immunity to SCC.

IV. PROCEDURE AND EXPERIMENTAL RESULTS

A. Less Corrosive Modifications of A.I. Test

The tests evaluating four modifications of the Federal Method 823 Alternate Immersion (A.I.) test were made using the first seven alloy-temper combinations listed in Table I, four having a relatively low resistance to SCC in the short-transverse direction, and three relatively high resistance. This assortment of alloys was selected to permit a comparison of the test variants with regard to both the detection of SCC susceptibility and the avoidance of non-typical failures in resistant alloys. All tests were made with 1/8" diameter tensile specimens, oriented in the

short-transverse direction.

Triplicate unstressed specimens were exposed for 5, 10, 30, 60 and 90 days and then were evaluated by determination of loss in tensile strength and weight. Additional unstressed specimens were provided for metallographic examination and tensile testing, concurrent with similar evaluations of stressed specimens.

Stressed specimens were loaded in the ARL standard stressing frame, subsequently referred to in this report as Frame A. Both the specimen and frame are shown in Figure 1. These specimens were exposed to failure or for a maximum of 90 days.

For low resistance alloys, five specimens were exposed at stresses of 8 and 20 ksi. When the time of the third failure permitted, exposure of the remaining two unfractured specimens was terminated and the specimens were metallographically examined or tensile tested. Two unstressed specimens were provided as controls.

For high resistance alloys, eleven specimens were exposed at stresses of 75 and 90% Y.S. When the time of the first and third failures permitted, four unfractured specimens were removed from test and metallographically examined or tensile tested. Eight unstressed specimens were provided as controls.

Stressed specimens were evaluated by the number surviving 90 days, by time to failure and by loss in tensile strength.

The specimens were exposed by alternate immersion (10 minute immersion plus 50 minutes drying per hour) to the five solutions listed below. The surrounding air temperature (80 ± 2°F)

and relative humidity (45 ± 6%) were controlled per Federal Test Method 823. Solutions were changed monthly.

a. 3.5% NaCl using reagent grade salt and deionized water. This is the <u>standard</u> solution per Federal Method 823, conducted to provide a basis of comparison.

b. Solution as per Method 823 but with a ten minute immersion once every two hours, rather than the normal once per hour.

c. 3.5% NaCl using reagent grade salt and synthetic New Kensington tapwater (deionized water plus 0.215 g $CaSO_4 \cdot 2H_2O$ + 0.013 g $MgSO_4 \cdot 7H_2O$ + 0.050 g $NaHCO_3$ per liter of solution). In this case the test variant is the water used to make the 3.5% NaCl solution. A synthetic tap water was used because previously tests were conducted in a solution made with New Kensington tap water and less pitting corrosion was encountered than in current tests using high purity deionized or distilled water per Method 823. The actual tap water itself was not used because it would not be available to all test facilities, also its composition varies seasonally with the amount of rainfall. The composition evaluated is typical of New Kensington tap water.

d. Solution as per Method 823 but with the addition of 0.008% Benzotriazole. This is a copper chelating agent that helps to prevent copper dissolved from the corroding alloy from redepositing on the specimen surface. The 0.008% concentration was selected after pilot tests (reported in the Tenth Quarterly Report)[5] had indicated this was about the maximum concentration that could be used without retarding the ability to detect SCC.

e. Synthetic ocean water per ASTM D-1141-52, Formula A as the corrodent. Tests employing this solution had shown it causes considerably less pitting than 3.5% NaCl, but there is some question about its ability to detect low degrees of susceptibility to SCC.

All tests other than the synthetic ocean water were conducted in what is called a "pump-in drain-out" A.I. unit. In this unit the specimens remain stationary about 1/2 inch off the bottom of a plastic tank and the solution is pumped into the tank and drained out. The synthetic ocean water tests were made with a small (2 ft. diameter) Ferris wheel. The principal difference between the two A.I. techniques is tnat drying conditions tend to be more rapid in the Ferris wheel.

The results obtained on the unstressed specimens are reported in Table II and those on stressed specimens in Table III.

B. Size of Specimen and Stiffness of Stressing Frame

It was realized at the onset of this extension to the contract, that altering the corrosive environment might not be wholly effective; or that even it it was, considerably more work would have to be performed to prove the validity and usefulness of such a change. Because no particular type or size of SCC specimen is as yet required by material specifications, an increase in specimen diameter from 1/8 to 1/4 inch was proposed as a more direct and perhaps simpler method of reducing the undesirable effect of pitting. This increase in specimen size is not enough to involve metallurgical differences in the material sampled; hence, the depth of pitting progresses at the same rate for both

sizes of specimens. The larger specimen should, therefore, tolerate a longer exposure period before the flaw size caused by pitting corrosion becomes critical.

On the other hand, it is probable that the larger specimen may also require a longer exposure period to cause failure by SCC for one or both of two reasons. First, if a certain level of stress-intensity at the base of a pit or site of corrosion is required to initiate a stress-corrosion crack, then the 1/4-in. specimen will require a longer induction period. Second, once SCC has initiated, the crack in the 1/4-in. specimen must propagate to a greater depth to reach critical flaw size and cause ultimate failure.

Another factor to be considered is that increasing the specimen size generally requires a larger stressing frame. Depending on the elastic compression of the side pieces, the bending of the cross pieces, and the deformation of the threaded connections, these stressing systems have stiffnesses that are intermediate between the two extreme methods of loading: (a) dead weight (constant load) and an infinitely stiff fixture (constant deformation). Stiffness of the frame-specimen combination can have an appreciable effect on the failure time for conditions where corrosion or cracking, or both, are general[6]. This effect is believed to be slight, however, for alloys and tempers that are susceptible to rapidly propagating SCC, particularly under conditions causing localized corrosion or cracking such as are encountered in alternate immersion tests of heat-treatable aluminum alloys. In order to extend information of this type developed

previously[7], compliance tests were made with the combinations of specimens and frames used for the SCC tests.

Stress-corrosion tests evaluating specimen size and stiffness of the stressing frame were made with five alloy-temper combinations, two of which have relatively low resistance to SCC in the short-transverse direction and three relatively high resistance.

All test specimens were oriented in the short-transverse direction. Two sizes of tensile specimens and stressing frames were used, and the dimensions of these are shown in Figure 1. The 1/8" specimen and Frame A are the combination normally used by Alcoa, while the 1/4" specimen and Frame B are adaptations received from MSFC. The 1/8" specimen was stressed in both sizes of frames, while the 1/4" specimen could be stressed only in Frame B.

The overall scope of the program was the same as was used to investigate the corrosivity of the environment except that specimens were exposed only to 3.5% NaCl alternate immersion per Federal Method 823.

Data obtained with unstressed specimens are listed in Table II and those with stressed specimens in Table IV. It should be noted that tests of the two sizes of specimens in Frame B were made in a single A.I. run, while those of the 1/8" specimen in Frame A were made in a separate A.I. run.

V. DISCUSSION

A. Stress Corrosion Performance

1. Effect of Corrosiveness of Environment

a. Unstressed Specimens

A relative comparison of the general corrosiveness of the various A.I. procedures can be made from the tensile strength loss and weight loss data obtained on the unstressed 1/8-in. specimens (Table II). Certain of these data are plotted in Figure 2 for alloys 2024-T351 and T851 and 7075-T651 and T7351 to illustrate observed trends.

The only A.I. modification that consistently was less corrosive than Method 823 was use of synthetic ocean water. This procedure caused negligible weight loss on all alloys and low loss in strength on all alloys other than 5456-sensitized. The reason for the relatively high loss in strength of the 5456-sensitized is the selective intergranular corrosion that appreciably reduced the net cross-section without removing appreciable metal.

The addition of 0.008% Benzotriazole significantly reduced weight loss over the entire 90 day exposure but reduced loss in strength only for the first few weeks of test. This observation on strength loss was also made in an independent Alcoa investigation and it was thought that the diminishing inhibition might merely be the result of depletion of the Benzotriazole. A retest was made in the Alcoa investigation using weekly solution changes and a slightly higher concentration of Benzotraizole (0.01%). The end results were unaltered, however, showing a retardation of corrosiveness only for the initial exposure (Figure 3).

The other two A.I. modifications (use of a 10/110 minute cycle or synthetic tapwater) appear to be about as corrosive as Method 823 showing similar, and often higher, per cent losses.

b. Stressed Specimens

The stress-corrosion data obtained in these A.I. modifications (Table III) are compared graphically in Figure 4 on the basis of exposure time required to cause the third failure. Because not all of the 5 or 11 replicate specimens were exposed to failure, the time of the third failure was used as an approximation of the median failure time. Data for alloy 5456-sensitized are not plotted, as these specimens failed rapidly in all environments.

As regards the low resistance alloys, all five A.I. procedures readily detected SCC at the 20 ksi stress at which these alloys are definitely susceptible. At the 8 ksi stress, which approaches the critical stress required for SCC of the low resistance alloys, the Benzotriazole procedure appeared less able to detect susceptibility than did Method 823, while the other three experimental modifications detected susceptibility sooner than Method 823. Additional tests are required, however, before it can be concluded that these differences at the 8 ksi stress are real and not merely random scatter in time to failure. With the extent of testing performed, the most probable conclusion is that all five procedures have similar ability to produce SCC in low resistance alloys.

The corrosiveness of the environment had more of an effect on the SCC performance of the higher resistance alloys. The criteria used to decide the suitability of an A.I. procedure for these alloys was how well the method reproduced the performance

observed in natural environments for tests of 1/8-in. specimens in Frame A. The results, discussed below, indicate that no one method is ideal (Figure 5).

Two of the modified procedures, 10/110 minute cycle and solution made with synthetic tapwater, gave essentially the same results as Method 823. This is not surprising in view of the fact that their corrosiveness proved to be similar. In these three procedures alloy 2024-T851 failed rapidly by SCC (Figure 6) at both stress levels, which is consistent with performance in seacoast atmosphere. However, all three methods failed 7075-T7351 (Figure 7) and the 7XXX-T7351 (Figures 8 and 9) plates by a non-typical transgranular mode. This is not representative of atmospheric performance because 7075-T7351 in these and in other tests has not failed even after many years, and while 7XXX-T7351 did fail, it was by true intergranular SCC in industrial atmosphere (Figure 10) and by a mixed-mode failure process involving a certain amount of SCC in seacoast atmosphere (Figure 11).

The synthetic ocean water environment did not produce failures in any of the three resistant alloys, though small transgranular cracks were detected metallographically in 7XXX-T7351. As such this solution permitted 7075-T7351 specimens to complete test but did not detect the susceptibility to intergranular SCC in 7XXX-T7351. Somewhat lesser ability to detect SCC is also indicated by the fact that the performance of 2024-T851 in this environment was equivalent to performance in inland industrial atmosphere rather than in seacoast atmosphere. It appears, therefore, that use of this solution would greatly minimize the occurrence

of transgranular cracking and readily detect marked susceptibility to SCC such as for the 2024-T351 and 7075-T651 plates but may not detect slight susceptibility such as in the 2024-T851 and 7XXX-T7351.

Finally, the Benzotriazole additive still permitted the slight susceptibility of 2024-T851 to be detected. However, while it retarded the initiation of transgranular cracking it did not prevent it. The independent tests conducted by Alcoa on the 7XXX-T7351 plate and other experimental alloys confirmed that this procedure was not effective in preventing transgranular failures.

In summary, therefore, two of the modified procedures did not significantly alter the corrosiveness nor the SCC performance of Method 823. The other two procedures did reduce the corrosiveness and hence permitted somewhat longer exposure before transgranular cracking was encountered, but they did not prevent transgranular cracking. Also the indication is that use of synthetic ocean water might decrease somewhat the ability to detect slight susceptibility to SCC. This would be a serious disadvantage in either alloy development or quality control of production lots. In alloy development this could lead to erroneous conclusions as to the degree of SCC resistance achieved and the safe level of stress that could be applied. Also it would limit the ability to detect minor differences between proposed alloys or tempers. Reduced sensitivity would be the concern in quality control tests where the usual problem is detection of a lot with marginal performance, rather than a gross malpractice.

An additional point to consider is whether excessive corrosiveness can be circumvented by limiting the length of exposure to an appropriate period for which the reduction in cross-section and strength is tolerable, but which is still adequate to detect susceptibility to SCC. It has been shown, for example, that a 30 day exposure to A.I. will amply detect intergranular SCC in many aluminum alloys(8). While the data in this contract are limited, it is evident that this is only a partial solution to the problem. A 30 day exposure for alloy 7075 is a workable procedure and, in fact, is specified in material specifications for the T73 temper(9). This length of exposure will detect any appreciable susceptibility to intergranular SCC in 7075, such as for the T651 temper, yet it is short enough to preclude a high occurrence of transgranular cracking. However, for certain alloys, such as the 7XXX-T7351 plate in this contract (Figure 4), the maximum exposure that could be tolerated without appreciable occurrence of transgranular cracking is too short to ensure adequate detection of SCC in any susceptible items.

In the preceeding discussion it has been assumed that a single "optimum" A.I, will be adequate for all these types of alloys. It is apparent, however, that for certain alloys, such as the 7XXX-T7351 plate in this contract, the A.I. test is not a reliable procedure because it does not fully reproduce the same mode of failure observed in natural environments. Independent tests by Alcoa on various plate alloys including the 7XXX-T7351 plate in this contract have shown that a 4 day total immersion in

boiling 6% NaCl solution sometimes reproduces performance in natural environments better than the alternate immersion test (Figure 12). A sample of these data are shown in Table V. The boiling salt test has not had industry wide acceptance, however, primarily because of unaccountable inconsistency in repetitive test runs.

2. Effect of Specimen Size and Stiffness of Stressing Frame

a. Low Resistance Alloys

Only limited analysis could be made of results of the two low resistance alloys, 2024-T351 and 7075-T651. Considering first the tests of both specimen sizes in Frame B, results (Table IV) were about as might be predicted. At the 20 ksi level both sizes of specimens failed, with the 1/4" requiring slightly longer exposure times. At the 8 ksi stress, the 1/4" specimen was less prone to failure, with the 7075-T651 specimens surviving the 90 day exposure and 2024-T351 specimens failing only during the last month of test. Although the 1/4" specimens of 7075-T651 did not fracture, metallographic examination showed that they did, in fact, contain numerous stress corrosion cracks; their cracking also was reflected by the relatively high loss in tensile strength of 77% compared to about 30% for specimens exposed 90 days with no stress.

It was expected that the 1/8" specimens in Frame A would have the shortest times to fail because it was anticipated that the stiffness of this specimen-frame combination would be the lowest of the three that were used. However, at the 20 ksi stress they had the longest average failure times and were in the middle

position at the 8 ksi stress. As mentioned in the Procedure, these specimens were exposed at a different time and the observed longer specimen lives may merely be run-to-run variability that is sometimes encountered with the A.I. test. This same set of data was used in the previous discussion of corrosivity of the environment. There too, they seem to be slightly out of line. Instead of showing the shortest failure times, they tended to show somewhat longer failure times than the other A.I. modifications, that were intended to be less corrosive.

b. High Resistance Alloys

The effect of specimen size and stiffness was in better agreement with theoretical predictions for the three alloys with higher resistance to SCC. For these alloys the two sets of 1/8" data are quite similar, while longer failure times occurred with 1/4" specimens (Table IV).

Alloy 2024-T851 is known to have some susceptibility to SCC at the very high stresses used and this was detected with all three specimen-frame combinations. Use of a 1/4" specimen seems an appropriate procedure for this alloy provided tests are conducted for a minimum of 30 days. Additional tests at lower stress levels are needed to determine whether the 1/4" specimen assembly would indicate the same threshold stress as the 1/8" specimen assembly.

On the opposite end of the scale, alloy 7075-T7351 has been shown to be virtually immune to SCC in atmospheres. Alternate immersion tests of 1/8" specimens in either size frame could, therefore, be misleading if fractured specimens are not examined

metallographically to establish the failure mode. Use of the 1/4" specimen would reduce the possibility of mistaking fractures resulting from pitting and transgranular cracking for SCC in tests conducted beyond 30 days.

The possibility of reduced sensitivity in the detection of marginal susceptibility must be resolved before larger specimens are used indiscriminately for quality control of 7075-T7X temper products. Additional tests are needed to establish whether a larger specimen would permit a long enough test period to detect any marginal items and yet prevent, or greatly minimize, transgranular fracturing. Tests by a joint Aluminum Association-American Society for Testing Materials task group[10] are currently studying this problem using 2-1/2" thick 7075 plate in the T651, T7X51 and T7351 tempers.

The 7XXX-T7351 plate did fail by intergranular SCC after long exposure to atmospheres (Table V), (Figures 10 and 11). Consequently none of the accelerated tests made on this plate predicted atmospheric performance because all caused failures only by a transgranular mode (Figures 8 and 9). Use of a larger specimen did not improve this situation. In fact, use of the 1/4" specimen had surprisingly little effect at the 90% Y.S. stress, though it did lengthen specimen life at the 75% Y.S. stress. It is concluded, therefore, that the alternate immersion test is not suitable for this alloy.

For the three high resistance alloys, stressed specimens removed from test prior to failure were tensile tested to evaluate incipient stress corrosion effects. Figure 13 shows the strength

after exposure of unstressed and stressed specimens, combining stressed specimen data for the two stress levels and for both sets of 1/8" specimens. The two applied stress levels (90 and 75% Y.S.) are indicated by horizontal dashed lines. Some observations made on these data are:

1. All curves for unstressed specimens show a marked decrease in the rate of corrosion with exposure time whereas, in general, those for stressed specimens do not.

2. For a given exposure period the reduction in strength of an unstressed 1/4" specimen was only 1/2 to 2/3 of that of an unstressed 1/8" specimen.

3. Application of stress caused a marked acceleration of the decrease in strength for the 1/8" specimens of all three alloys and for 1/4" specimens of 7XXX-T7351 alloy. This marked decrease is primarily the result of small cracks in the specimens, as noted visually on the fractured faces of the specimens and confirmed by metallographic examination (Figure 14).

4. Intergranular SCC was detected only in 2024-T851 and failures of this alloy began to occur before the breaking strength of the specimen was reduced to the level of applied stress. For the other two alloys, failures did not occur until after the reduction in breaking strength was such that failure by mechanical breaking could be expected (Figure 13).

5. The reduction in strength of unstressed specimens of 7075-T7351 and 7XXX-T7351 was similar, indicating the rate of pitting corrosion is comparable for the two alloys. However, the 7XXX-T7351 specimens showed much greater strength loss than

did 7075-T7351 when corroded under stress. Specimens of both alloys developed transgranular cracks, but the cracks apparently initiated earlier and grew faster in specimens of the 7XXX-T7351 alloy.

6. Based on the original area, many of the final strengths of unfractured specimens were well below the level of applied stress. One might be tempted to conclude that the intended level of stress simply had not been applied. This is not the case because strain measurements were made on all specimens during loading. The intended stress is present at least at the point where the strain follower was positioned. While there may be some variation in stress around the circumference of the specimen, it would not be of the magnitude indicated by the final corroded strengths. The actual reason is related to relaxation caused by the occurrence of cracking at multiple sites (Figure 14) as discussed in the next section.

In summary, for alloys for which the alternate immersion test is a valid test method, use of a larger specimen may be a useful procedure to minimize transgranular cracking and still detect susceptibility to intergranular SCC. However, all tests were made on alloys with either relatively low or high resistance to SCC, and further tests are needed of alloys and tempers with intermediate resistance. Use of the larger specimen was of no advantage for alloys for which alternate immersion is not an appropriate environment.

B. Compliance of Specimen - Stressing Frame Assemblies

1. Effect of Alloy and Temper

As a localized crack or pit develops in the surface of a tension type stress-corrosion specimen, the average stress on the net section containing the flaw increases until the fracture strength is reached and the specimen breaks. The magnitude of the average net stress for a given reduction in cross sectional area will be a function of the alloy and the stiffness of the specimen-frame assembly. The variations in net section stress with reduction in area were investigated for a variety of alloys with 1/8-in. diameter short-transverse tensile type stress-corrosion specimens stressed in Frame A. Local flaws in the specimens were simulated by machining a pair of sharp V-notches on opposite sides at the midlength of the specimens, as shown in Figure 15. Specimens having notches to provide nominal reductions in area ranging from 0 to about 80 per cent were prepared in a group of alloys (Table B-1) chosen to provide a range of strength and notch toughness. The procedure used to calculate the stresses is outlined in Appendix B.

Figure 15 shows the increase in net section stress with per cent reduction in area for the various alloys, starting with initial stresses of 20, 40 and 60 ksi on unnotched specimens. The intersections of these curves with the notch tensile strength curves indicate the per cent reduction in cross section area required to cause fracture of each alloy under these test conditions. It is shown that for a relatively low initial stress (20 ksi) about 80% reduction of area was required for fracture of all of the alloys. However, for higher initial stresses the per cent

reduction of area to cause fracture increased appreciably with the notch tensile strength of the alloy. For example, for an initial stress of 40 ksi the per cent reductions ranged from about 20 to 60%, with the alloys lining up as follows: 5083-H131, 6061-T651, 2219-T37, 7178-T651, 7075-T7351, 7039-T63, 7075-T651 or 7079-T651.

2. Effect of Type of Surface Flaw

Additional specimens in alloys 2219-T37 and 7178-T651 were notched either circumferentially or on one side with a sharp V-notch to simulate other types of corrosion flaws. The average net section stresses and notch tensile strength for these specimens are shown in Figures 16 and 17. Because of the stress concentration at the notch due to bending, the notch tensile strengths of single edge notched specimens are considerably lower than those of circumferential and double edge notched specimens. Thus, it can be concluded that the distribution of stress corrosion cracks or pits can have a marked effect on times to failure; specimens with flaws developed on only one side will fail much sooner than specimens for which corrosion tends to occur symmetrically around the specimen.

3. Effect of Specimen-Frame Assembly Stiffness

The stiffnesses of various specimen-frame assemblies of interest are compared in Figure 18. Assemblies of the 1/8-in. specimen in Frames A and B exhibited almost constant stiffness over a wide range of applied stress. However, with the larger diameter (stiffer) specimens, the assembly stiffness was not constant, but increased with higher applied stress. This is due

to the fact that the stressing frames are designed so that stresses are induced in the specimens by the inward movement of the wedge-shaped side pieces; the greater the inward movement the higher the stress. Inward movement decreases the span of the end pieces, and thus increases stiffness. In comparing the stiffnesses of the several assemblies used in the stress-corrosion tests discussed in a previous section, it is noted that the stiffness was about the same whether the 0.125 in. specimen was stressed in Frame A or Frame B. However, the 0.250 in. specimen - Frame B assembly was about four times as stiff as the 0.125 in. specimen assemblies. It should be mentioned that the accuracy of the specimen-frame assembly determinations was such that stiffness differences of $\pm 1 \times 10^4$ lb./in. probably are not significant.

Because the energy stored in a loaded specimen-frame assembly is elastic, one might expect from Hooke's law that the stiffness of the assembly would influence the rate of increase of the net section stress during the growth of corrosion flaws, which in turn, could affect the time to fracture of the test specimen. The range of stiffnesses of the several assemblies shown in Figure 18 was not very large, so a somewhat wider range was studied to determine the effect on the net section stress. These data are shown in Figures 19 and 20 for 1/8-in. diameter specimens of 2219-T37 and 7178-T651 containing double edge V-notches.* The rate of increase of the net section stress did vary with

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* In Figures 19-21 the stiffness of the 1/8-in. specimen - Frame A assembly (6.4×10^4 lbs./in.) is designated as K_o and other stiffnesses are expressed as multiples of K_o.

assembly stiffness, but only slightly, depending upon the notch tensile strength of the alloy and the magnitude of the initial stress. Although not plotted, the effect would be even less for more severe stress concentrators, exemplified by the single edge V-notch. Thus, the actual increase in the time to fracture would depend upon the rate of propagation of cracks in the specimens and the pattern of the surface attack. Unfortunately the data shown in Table IV for three different specimen-frame assemblies do not provide a comparison of stiffnesses without also including the variable of specimen diameter. Nevertheless, the data for 2024-T351 and 7075-T651 alloy specimens stressed at 20 ksi, which exemplify a high rate of propagation of SCC, show that in such cases the combined effects of increased specimen diameter and increased stiffness were negligible.

It was shown previously[6] that the corrosion pattern could have a pronounced effect on the time to fracture of an 1/8-in. diameter specimen stressed in Frame A; such an effect occurs when the corrosion becomes very uniform as in the case of general dissolution of the surface or general intergranular attack. Figure 21 shows the change in average tensile stress on the net section for different methods of loading when the effective net section area is reduced uniformly. For dead loading the net section stress increases rapidly to fracture of the specimen just as it would in the case of localized cracking. For the other extreme, an infinitely stiff stressing frame, the stress does not change and the specimen would not fracture. For a standard 1/8-in. specimen in Frame A the net section stress increases and

then levels off without fracture of the specimen. Increasing the specimen-frame assembly stiffness, as to 5 K_o, moves the curve downward toward the horizontal line for the perfectly rigid frame. Considerable stress corrosion testing experience has shown, however, that there are other corrosion and cracking patterns that would give different curves, such as the dashed line for K_o. This is exemplified by the performance of highly stressed specimens of 7075-T7351 (Figure 14) or specimens of 7075-T651 stressed to very low levels (8 ksi: Table IV). In testing items such as these, increasing the stiffness of the specimen-frame assembly could increase the time to fracture markedly and possibly result in no fracture during test, as suggested by the dashed line for 5 K_o. The same effect, of course, would be obtained by increasing the diameter of the test specimen.

4. Effect of Variations in Specimen Design

Another way to alter the stiffness of the specimen-frame assembly is to change the dimensions of the specimen. Calculations of stiffness were made for variations of diameter and length of the test section of the nominal 0.125 in. specimen stressed in Frame A. It is shown in Figure 22 that the stiffness can be increased both by increasing the diameter and decreasing the test length; increasing the diameter had a slightly larger effect. By extrapolation of this diagram it can be estimated that modification of the 0.125 in. specimen to a diameter of 0.225 in. with a test length of 1.25 in. would increase the stiffness to about 12 x 10^4 lb./in. when stressed in Frame A. This corresponds

closely to the assembly stiffness determined by compliance experiment as shown in Figure 18. Thus, it is indicated that, (a) the stiffer assembly of the 0.225 in. specimen with Frame A is a result of the changes in specimen size, and (b) that the further increase in stiffness for the assembly of the 0.250 in. specimen with Frame B is a result chiefly of the modification of the stressing frame.

C. Interpretation of Transgranular Cracks

Stress-corrosion cracking of susceptible aluminum alloys has characteristically been intergranular or interfragmentary. In other metal systems, the path of SCC is intergranular for some alloys and transgranular for others. In some metal alloy systems, either type of cracking can be obtained through variations in metallurgical structure of the metal or change in environment. It is conceivable that the path of SCC could be similarly influenced in aluminum alloys. Transgranular cracking in highly stressed high strength aluminum alloy test specimens exposed to the 3.5% NaCl alternate immersion test has occurred particularly with experimental 7XXX-T7 alloys. This is a matter of considerable concern because it is not known whether to classify them as an area-reduction corrosion failure (mechanical) or a special case of SCC.

Transgranular cracks in highly stressed (75% Y.S.) short-transverse specimens of 7075-T7351 products were noted about ten years ago in the 3.5% NaCl alternate immersion test. Failures of specimens containing such cracks occurred after relatively long exposures during which severe pitting occurred. Because this mode of cracking was unfamiliar in aluminum alloys

it has been regarded with suspicion, and specimen failures associated with transgranular cracks have generally been classified as "non-typical", and considered to have resulted from mechanical cause, possibly tensile overload or stress rupture. This decision was influenced considerably by metallographic and fractographic studies made of such failures in a previous contract investigation[11]. The results of the alternate immersion tests performed in that investigation and the subsequent atmospheric exposure tests are given in Table VI. It is noteworthy that there has been no fracture of the fifteen 1/8-in. tensile bars and the five rings during 7-1/2 - 8 yr. exposures to seacoast and industrial atmospheres. These data and other similar test results ranging up to ten years in both seacoast and industrial atmospheres obtained by Alcoa Research Laboratories have created doubts about the practical significance of such cracking of small specimens subjected to a high sustained tensile stress and exposed to a very corrosive test medium.

Environmental conditions have a marked influence on the tendency for transgranular cracking of 7XXX-T7 alloy specimens. Transgranular cracking has not been observed with any alloy in the industrial atmosphere. Rather, experimental alloys that develop transgranular cracking under high stresses in the A.I. test may develop intergranular cracking at similar stresses in the industrial atmosphere; in a seacoast atmosphere cracking may be a combination of intergranular and transgranular (Table V). In certain other test media that have very little corrosive effect on the aluminum surface, such as boiling 6% sodium chloride,

intergranular SCC may develop (Table V). On the other hand, all environments that cause severe pitting and failure of highly stressed 7XXX-T7 specimens do not cause transgranular cracking. For example, unpublished work by J. D. Walsh at ARL has shown that exposure to an acidified sodium chloride solution by total immersion caused severe pitting and mechanical overload failure without secondary cracking, whereas, exposure to the same corrodent by alternate immersion caused severe pitting and failure with auxiliary transgranular cracking. Thus, it seems that transgranular cracking is not necessarily associated with simple tensile overload. It has been hypothesized that the transgranular cracking results not from simple mechanical overload, but from a repetitive wedging action caused by alternate wetting and drying of insoluble corrosion products which form in pits during the A.I. test cycle.

In this investigation transgranular cracks occurred in specimens of both 7075-T7351 and 7XXX-T7351, as shown in Figures 7-9. Fractographic examination of transgranular cracks in a failed specimen of 7XXX-T7351 alloy showed that the cracks had brittle crack characteristics quite different from the dimpled surface of a tension fracture (Figures 23 and 24). This evidence indicates that such failed specimens had not failed simply by tensile overload; if they had, the whole fracture would show the dimple rupture characteristic of a ductile tension failure. These cracks bear considerable resemblance to Stage 1 fatigue failure in aluminum alloys[12] and to the transgranular stress-corrosion cracks in austenitic stainless steel[13]. Additional evidence

is needed to decide whether these transgranular cracks are some kind of a mechanical crack or whether they are stress corrosion cracks. Unless conclusive evidence of a stress-corrosion mechanism is obtained, it seems advisable to continue to refer to such transgranular cracks in aluminum alloys as "mechanical".

VI. STATE OF STRESS

A limited fundamental study was undertaken to (a) investigate whether simple tension is the exclusive stress state that is necessary to cause stress-corrosion cracking and (b) illustrate possible interactions of stress state and stress orientation in a product with directional grain structure.

A. Procedure

Various elastic stress states were obtained by loading hollow round specimens, Figure 25, in either tension, compression or torsion. Thin-wall, hollow, rather than solid, specimens were used to minimize (a) the time interval between crack initiation and complete failure and (b) the variation in stress through the wall.* Tension loads were obtained with Frame A, Figure 26. Compression loads were obtained by means of a threaded steel rod extending through the specimen, with washers and nuts tightened against the ends of the specimen. Torsion loads were obtained using the fixture shown in Figure 27. Stresses were calculated from strain measurements made with electrical resistance

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* The stresses in a solid cylinder loaded in torsion vary linearly from a maximum at the surface to zero at the center.

strain gages bonded to the outer surface of the cylinder or with a mechanical extensometer clipped onto the specimen.

Stress-corrosion tests were performed in the 3.5% NaCl alternate immersion test per Federal Test Method 823. The cores of all specimens were filled with a polysulfide-type caulking material to avoid corrosive attack on the inside surface. The grip ends of the specimens and the loading frames were coated with paint* to avoid crevice and galvanic corrosion. The directional grain structure present in the 2.50-in. thick 7075-T651 alloy plate used in this investigation is illustrated by the micrographs in Figure 28.

B. Results

The orientation of test specimens and results of the tests are summarized in Figure 29. Metallographic examination of representative failed specimens revealed that the material was susceptible to a combination of pitting and intergranular attack and that all failures resulted from intergranular stress-corrosion cracking that followed the directional grain structure (Figures 30-32).

C. Discussion

The normal and shear stresses acting on various planes in the specimens can be represented graphically by means of Mohr's circle(14). Mohr's circles for specimens loaded in tension, compression and torsion are shown in Figure 33. To demonstrate the construction of Mohr's circle, consider the case of tension loading, Figure 33(a). In general, for any combination

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* Gates Liquid Neoprene paint (type GACO-N-700A).

of biaxial stresses at a point there are two perpendicular planes, passing through the point, on which only normal stresses exist; these stresses are called principal stresses. All other planes passing through the point will have both normal and shear stresses acting on them. For the case of axial tension, the maximum principal stress, σ_1, which is equal to the load divided by the cross sectional area, acts on plane P_1, normal to the longitudinal axis; while the minimum principal stress, σ_3, which is equal to zero, acts on plane P_3, parallel to the longitudinal axis. To construct Mohr's circle, lay off the principal stresses, σ_1 and σ_3, along the horizontal axis. Tension stresses are considered positive and are plotted to the right, whereas compressive stresses are considered negative and plotted to the left. Now construct a circle with its center on the σ-axis and located at a distance $1/2\ (\sigma_1 - \sigma_3)$ from the origin. It can be shown[14] that the normal and shear stress acting on a plane in the specimen, inclined at an angle θ from the plane on which σ_1 acts, is represented by the coordinates of the point on the circumference of Mohr's circle which is intersected by the radius making an angle $2\ \theta$ with the σ axis. Thus, referring to Figure 33(a), the normal and shear stress are both equal to $1/2\ \sigma_1$, on planes P_2 and P_4, which are inclined at 45° to the specimen axis. The stress state in the specimen loaded in compression is similar to that in the specimen loaded in tension. In the case of torsion loading, only shear stresses act on planes P_1 and P_3; while only normal stresses act on planes P_2 and P_4.

Mohr's circles for the specimens tested in this investigation

are shown in Figure 29 with the test results. There are several interesting observations which can be made from these Mohr's circles concerning the effect of specimen orientation and type of loading on the stresses acting on plane P_1, this being the most critical plane. First consider the case of tension loading of the specimen. For Case A1, plane P_1 is stressed in tension; for Case A2 this plane is stressed in tension and shear; while for Case A3 and A4 there is no stress acting on plane P_1. Similar observations may be made for the case of compression loading, Cases B1, B2, B3 and B4, except that the normal stresses are compressive. In the case of torsion loading, plane P_1 is stressed in pure shear (no normal stress) when the specimen is oriented in either the short transverse (Case C1), long transverse (Case C3) or longitudinal direction (Case C4). Torsion loading of the specimen at 45° (Case C2) is a special case, in that the stress state on plane P_1 varies around the specimen. Determination of the stresses on plane P_1 involves the construction of Mohr's circle for a triaxial stress state. Without going into details, it can be shown that the stress on plane P_1 varies around the specimen as shown by Mohr's circles in Figure 34. It can also be shown that the maximum tensile stress occurs at location B, where the shearing stress is zero. Point D is stressed in pure compression, while points A and C are stressed in pure shear. All other points on plane P_1 are stressed with various combinations of normal and shear stress, with the normal stress always being lower than that at B.

Referring to Figure 29, the expected general observations

were confirmed; i.e., that stress corrosion failure can occur by torsion loading (Cases C1 and C2)[2] as well as by tension loading (Cases A1 and A2), but that no failures occurred under compression loading (Cases B1 and B2). The fact that failure occurred when plane P_1 was subjected to shearing stress but no tensile stress, Case C1, might lead to the conclusion that pure shear stress can cause stress-corrosion cracking. This conclusion appears to be substantiated by a comparison of times to failure for Cases A1 and A2, where for equal normal stresses the presence of a shear stress on plane P_1 results in a decrease in time to failure.

There may be another explanation for the results described above. This relates to the observation that although a crack will propagate predominantly along parallel grain boundaries the crack must continually branch to bypass certain obstructing grains. Assume that the rate at which the crack propagates along the branch planes is a function of the normal stress on such planes, and that shear stresses have no direct effect on crack growth. The normal stress on the branch plane will be a function of the type of loading on the specimen. Consider Cases A1 and A2 again, where the normal tension stress acting on plane P_1 is equal to 12.5 ksi. Now assume that a crack has propagated along a straight grain boundary for some distance from the surface along plane P_1, meets the edge of a grain, and must, therefore, branch at an angle of 22-1/2° to go around it. For Case A1, Mohr's circle shows that regardless of whether the crack branches to the right or to the left, the normal stress on

the branch plane is reduced to σ^1 (equal to 10.6 ksi). However, for Case A2 it may be seen that the normal stress on one of the branches is actually higher (16.9 ksi), than that on plane P_1. This could account for failure times for Case A2 being less than those for Case A1.* However, to explain failures for Case C1 with the assumption that shear stress has no effect on SCC, the entire crack propagation would have to occur along branch planes with no cracking on plane P_1 because of the absence of a normal stress on this plane. This does not seem very likely, and a more plausible explanation is that both the normal tension stress and the shear stress were contributory to stress-corrosion cracking, but that normal tension stress has a greater effect on crack growth rate than does shear stress. This observation is consistent with previous observations of Mears, Brown and Dix[(2)] in tests of a cast product with a non-directional grain structure. They showed that torsion loading caused SCC, but that the cracking was in a 45-degree plane on which there was a normal tension stress equal to the shear stress on planes perpendicular to the longitudinal axis of the specimen. Thus, if there is an effect of the shear stress it is less than that of tension stress. Further work is required in this area.

Based on the above discussion, it would appear that time to failure should be equal for Case C2 and Case A1, for equal normal stresses, σ_1, on plane P_1. However, actual times to

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* To carry this discussion a little further, for Case A1, equal normal stresses on the two possible branch planes should not influence which of these planes the crack propagates on; while, for Case A2, if normal stress is the only consideration, then the crack should always branch into the plane between planes P_1 and P_4.

failure for Case C2 might be longer than anticipated for the following reason. The probability of a crack initiating in Case A1 is greater than in Case C2 since all points around the specimen in Case A1 are stressed to the maximum normal tensile stress, while only one point on the periphery of Case C2 specimen is stressed to the maximum tensile value. All other points on Plane P_1 in Case C2 are either stressed to a lower tensile value or are stressed in compression, as shown in Figure 34.

The performance of the compression specimens is of interest as no visible cracking developed on either the short-transverse (B1) or the 45° to long-transverse (B2) specimens during prolonged exposure. None would be expected on the short-transverse specimen, but, if shear stress has an appreciable effect, one would look for it on the 45° specimens (B2) because there were shear stresses on the critical P_1 plane. Metallographic examination of these specimens revealed intergranular corrosion (in addition to the severe pitting) just as in specimens loaded by the other methods. The examination also detected a single stress corrosion crack in one of the 45° specimens extending nearly through the wall thickness, but showed none in the short-transverse specimen (Figure 32). Thus, it appears that there was a SCC effect associated with the shear stress but that it was repressed by the normal compression stress. The use of compression stresses to prevent SCC is, of course, well known.

Bollani recently reported[15] some identical findings with regard to torsion loading of hollow-core specimens machined

from 7075-T651 alloy plate. A portion of his data is reproduced in Figure 35. These data confirm that shear stress can cause SCC and indicate that the threshold shear stress may be similar to that for short-transverse tension stress.

The graphs in Figure 35 indicate shorter times to failure and possibly a slightly lower threshold stress for short-transverse specimens (Case C1) than for longitudinal specimens (Case C4). This is supported by the single C4 test conducted at ARL (Figure 29) showing a 21 day failure at a stress of 25 ksi as contrasted with failure times of 2, 3 and 5 days for C1 specimens at stresses of 25, 19.5 and 10 ksi. If the notation of time to failure was based on complete fracture (separation) of the specimen, there are two reasons why the short-transverse specimens might fail sooner: (1) For much the same reasons discussed previously for Case C2, the maximum shear stress on longitudinal specimens occurs only at two locations, on opposite sides of the specimen, where plane P_1 is normal to the specimen surface; at all other locations the stresses on planes parallel to plane P_1, are lower; and (2) crack growth in the axial direction of the specimen is limited by the larger section at the ends of the specimen.

These data for torsional loads imposed on specimens from a product with a highly directional grain structure and a low resistance to SCC in one of the directions (short transverse) have important implications for structural components. From a design point of view it is advisable to look at all sustained torsional load situations in such alloys as critical SCC situations.

This is especially pertinent to thin components which ordinarily do not experience short-transverse tension stresses. These results also suggest a method of performing short-transverse SCC tests on thin plates.

VII. CONCLUSIONS

The occurrence of SCC in any stress-corrosion test specimen requires the combination of a "susceptible" alloy and environment and an appropriate stress. The time to fracture of a tension-type stress corrosion test specimen depends upon several factors including the magnitude of applied stress, method of loading, the time to initiate SCC, the rate propagation of the SCC, the cross-section area of the specimen and the notch fracture strength of the alloy[16]. The probability and the time to fracture of such specimens loaded by the method used in this investigation depends to a marked degree also upon the corrosion pattern developed in the specimen and the stiffness of the specimen-stressing frame assembly. Moreover, fracture of the test specimen can occur in the absence of SCC for certain loading methods and corrosion patterns developed in the specimen simply by the reduction of cross-section area by corrosion. The determination of an optimum accelerated stress corrosion test method involves the combination of these factors into a procedure that provides a test with a clear end-point, good repeatability and a single interpretation of test failures. Neglect of the above considerations in the performance of such tests is likely to give ambiguous test results that can be quite variable and

lead to erroneous comparisons of test materials. The following conclusions were drawn from the work done in this investigation.

1. The corrosiveness of the 3.5% NaCl alternate immersion test per Method 823 can be markedly reduced by addition of a copper-chelating agent (0.008% Benzotriazole) or by using synthetic ocean water (per ASTM D-1141-52, Formula). With certain types of experimental 7XXX-T7 alloys, such as the one included in this program (X7375 + Zr + Ag), the 3.5% NaCl Method 823 alternate immersion test does not reproduce the same kind of SCC tendencies as atmospheric exposures, and these modifications do not improve the situation.

2. Either the use of a less corrosive modification of the corrodent or the substitution of a larger diameter of test specimen (1/4-in. for 1/8-in.) appreciably decreased the mechanical failures of specimens of 7075-T7351 and the experimental alloy 7XXX-T7351, but also increased the time to fracture of specimens of low resistance alloys and of 2024-T851 stressed to relatively low levels. Hence, threshold stresses determined with these modifications may err on the high side in comparison with the results of outdoor tests.

3. Alternate immersion exposure to 3.5% NaCl + 0.008% Benzotriazole of the 1/8-in. dia. X 2-in. long specimen in Frame A or B appears promising as a possible compromise for reducing the severity of pitting and minimizing the occurrence of mechanical failure of 7075-T7351 without appreciably sacrificing sensitivity to SCC of susceptible alloys; consideration should be given to a shorter exposure than the usual 84 or 90 days.

4. With the 1/8-in. diameter specimen stressed in the standard ARL frame (Frame A), the occurrence of different corrosion patterns can influence the average net section stress and the time to fracture over the full range of effects expected in shifting from constant load to constant deformation loading.

a. For a corrosion pattern with highly localized SCC or pitting, reduction of the net section area causes a rapid increase in the average net section stress until the specimen fractures, almost the same as with dead weight loading. The time to fracture will be longer for alloys with higher notch tensile strength but can be shortened appreciably by unsymmetrically distributed corrosion notches.

b. For a very uniform corrosion pattern resulting from general dissolution of the surface or general intergranular attack, reduction of the "net" section area causes only a limited increase in average section stress and the specimen will not fracture, approaching the performance for a constant deformation loading method.

c. However, when testing alloys with a limited susceptibility to SCC, such as 7075-T76, an intermediate corrosion pattern usually occurs. In this situation, a reduction in the net section area causes an intermediate rate of increase in the average net section stress, and both the probability of fracture and the time to fracture can be markedly influenced by the notch tensile strength of the alloy, the corrosion pattern, and the specimen-frame assembly stiffness.

5. The stiffness of the test specimen-stressing frame assembly, which is influenced by the diameter and length of the test specimen as well as by the rigidity of the stressing frame, has only a minor effect upon the stress-corrosion test results when the corrosion pattern is highly localized or is very uniform but can have an appreciable effect with intermediate corrosion patterns. Therefore, caution must be exercized in comparing stress-corrosion test results obtained with different sized specimens, and stressing frames.

6. Fractographic examination of the transgranular cracks that initiated at the bottoms of corrosion pits in highly stressed specimens of 7075-T7351 and 7XXX-T7351 alloys exposed to the 3.5% NaCl alternate immersion test revealed that they are not typical of simple tensile overload failures. These cracks have a marked resemblance to Stage 1 fatigue failure in aluminum alloys and also to the transgranular SCC in austenitic stainless steel. Additional studies of the cause of such cracks are needed, but unless conclusive evidence of a stress-corrosion mechanism is obtained, it seems advisable to continue to refer to such transgranular cracks in aluminum alloys as "mechanical".

7. Shear stress acting on a short-transverse plane can cause SCC in a product with a highly directional grain structure and relatively low resistance to SCC in the short-transverse direction, but the tendency is not as strong as for a tension stress acting normal to a short-transverse plane.

8. From a design point of view shear stress components should also be considered along with tension stress components. It is advisable to look at all sustained torsional load situations as critical SCC situations in relatively low resistance alloys regardless of the direction of any normal tension stresses.

Table I

IDENTIFICATION, TENSILE PROPERTIES AND CHEMICAL COMPOSITION OF ALUMINUM ALLOY PLATE EVALUATED IN NASA CONTRACT NAS 8-21487, PART II

Relative S.T. Resistance to SCC	Alloy-Temper	S. No.	Thick. In.	Long-Transverse T.S. ksi	Long-Transverse Y.S. ksi	Long-Transverse El. %	Short-Transverse T.S. ksi	Short-Transverse Y.S. ksi	Short-Transverse El. %
Low	2024-T351	366936	2-1/2	68.9	47.6	17.8	59.1	43.5	3.5
Low	5456-Sensitized	366657	2-5/8	----	----	----	44.1	27.7	4.5
Low	7079-T651	366259	2-1/4	78.9	70.1	12.8	76.2	65.1	2.0
Low	7075-T651	366938	2-1/2	80.2	71.7	8.0	74.8	66.6	2.0
High	2024-T851	366937	2-1/2	70.4	64.4	7.0	65.1	62.3	1.0
High	7075-T7351	366939	2-1/2	68.0	56.5	9.5	65.0	54.4	4.0
High	7XXX-T7351(1)	366688	2	----	----	----	68.9	60.8	3.0
Low	7075-T651(2)	367115	2-1/2	79.3	68.1	9.8	75.6	64.3	4.0

Alloy	S. Nos.	Chemical Composition - Per Cent (Remelt Analysis) Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Be	Ag	Zr
2024	366936, 366937	0.14	0.31	4.58	0.58	1.50	0.15	0.02	0.05	0.001	----	----
5456	366657	0.12	0.28	0.06	0.78	5.40	0.05	0.10	0.03	0.000	----	----
7079	366259	0.10	0.20	0.77	0.17	3.57	4.68	0.17	0.03	0.001	----	----
7075	366938, 366939	0.08	0.31	1.81	0.02	2.38	6.02	0.19	0.03	0.002	----	----
7XXX(1)	366688	0.08	0.28	1.47	0.01	2.29	5.76	0.00	0.14	0.000	0.35	0.13
7075(2)	367115	0.09	0.23	1.74	0.03	2.46	6.08	0.18	0.04	0.002	----	----

NOTES: (1) Alloy X7375 plus silver and zirconium.

(2) This plate used only for hollow-core specimens in State of Stress program.

Table II

PER CENT LOSS IN TENSILE STRENGTH AND WEIGHT OF UNSTRESSED SPECIMENS
AVERAGE OF TRIPLICATE SPECIMENS EXCEPT AS NOTED

		Per Cent Loss In Tensile Strength						Per Cent Loss In Weight					
				Environmental Variable(1)						Environmental Variable(1)			
Alloy	Exposure Period Days	Mthd. 823 1/4" Dia.	Mthd. 823 1/8" Dia.	10/110 Min. Cycle	Synthetic Tapwater	0.008% Benzo.	Syn. Ocean Water	Mthd. 823 1/4" Dia.	Mthd. 823 1/8" Dia.	10/110 Min. Cycle	Synthetic Tapwater	0.008% Benzo.	Syn. Ocean Water
2024-T351	5	16(2)	33	24	21	1	9	0.10(2)	0.18	----	----	----	----
	10	21	40	42	26	1	11	0.23	0.54	----	----	----	----
	30	28	57	64	51	12	15	0.78	1.00	1.59	0.95	0.00	0.00
	60	42	60	71	63	35	14	1.81	1.93	2.28	1.54	0.18	0.03
	90	38	69(3)	91(5)	43(5)	38	15	2.37	3.50(3)	4.62(5)	1.57(5)	0.34	0.00
5456-Sens.	5	--	48	24	44	6	3	----	----	----	----	----	----
	10	--	48	36	22	3	37	----	----	----	----	----	----
	30	--	59	43(3)	33	42	34(3)	----	0.37	0.04(3)	0.09	0.02	0.00(3)
	60	--	64(3)	53	35	39	70(5)	----	0.33	0.05	0.21	0.00	0.00(5)
	90	--	57	48	34(3)	45	46(3)	----	0.40	0.33(4)	0.26(3)	0.03	0.00(3)
7079-T651	5	--	1	0	1(2)	0	0	----	----	----	----	----	----
	10	--	7	4	2(2)	0	0	----	----	----	----	----	----
	30	--	22	13	7	13	0	----	1.33	0.42	0.65	0.24	0.00
	60	--	18	15	27(5)	13(4)	27	----	1.86	0.79	1.15(5)	0.30	0.00(2)
	90	--	13(5)	45(2)	(6)	11	28	----	2.43(4)	1.35	(6)	0.59	0.13
7075-T651	5	12	18	11	18	1	0	0.09	0.17	----	----	----	----
	10	14	30	20	18	6	0	0.24	0.24	----	----	----	----
	30	31	35	32	41	29	0	0.56	0.91	1.02	1.04	0.38	0.00(2)
	60	31	43	57	55(5)	56(2)	0	0.95	1.63	1.53	1.60(5)	0.50	0.18(2)
	90	19	60(3)	57	55(3)	60(3)	12(2)	1.66	2.24(3)	2.38	1.91(3)	0.71(3)	0.23
2024-T851	5	8	11	6	6	2	2	0.12	0.30	----	----	----	----
	10	10	28	15	11	3	2	0.25	0.68	----	----	----	----
	30	20	32(2)	34	43	20	2	0.63	1.07	1.28	1.27	0.70	0.00
	60	31	49(2)	60	(6)	27	4	1.32(2)	1.99	2.02	(6)	0.77	0.04(4)
	90	30	44	81	60	37	3	2.01	2.20	3.37	2.19	1.09	0.05(2)
7075-T7351	5	5	8	4	3	0	0	0.07	0.06(2)	----	----	----	----
	10	10	13	7	7	6	0	0.12	0.10	----	----	----	----
	30	10	19	15	16(2)	16	1	0.48	0.61	0.73	0.81	0.05(2)	0.00
	60	13	24	24	36	21	0	0.88	1.17	1.52	1.54	0.26	0.00
	90	15	24(3)	30	50	18	4	1.55	1.65(3)	2.61	1.97	0.38	0.02
7XXX-T7351	5	5(4)	11	3	6	0	0	0.10(4)	0.22	----	----	----	----
	10	7	16	12	10	4	0	0.21	0.41(2)	----	----	----	----
	30	11	19	22	18	12	0	0.60	1.29	1.42	1.13	1.03	0.00
	60	13	22	29	43(3)	29	0	1.28	2.25	2.31	2.05(3)	1.35	0.01
	90	15	32(3)	39	48(3)	33	1	2.21	3.16(3)	3.87	2.16(3)	1.60	0.13

NOTES:
(1) All 1/8-in. diameter specimens.
(2) Average of two specimens - value for third specimen considered an outlier.
(3) Average of two specimens - third specimen broke while attempting to remove protective caps from threaded ends.
(4) Value of a single specimen - other two specimens considered as outliers.
(5) Value of a single specimen - other two specimens broke during dismantling.
(6) No value - all three specimens broke during dismantling.

Table III

EFFECT OF ENVIRONMENTAL MODIFICATIONS OF THE 3.5% NaCl ALTERNATE IMMERSION FEDERAL METHOD 823 ON THE SHORT-TRANSVERSE RESISTANCE TO SCC. SOLUTIONS CHANGED MONTHLY 1/8-IN. DIAMETER TENSILE SPECIMENS LOADED IN STRESSING FRAME A (FIGURE 1)

Alloy	Environmental Variable	Fractured Specimens F/N (1)	Fractured Specimens Type(2) Failure	Fractured Specimens Days to Failure	Unfractured Specimens Days Exposed	Unfractured Specimens % Loss In T.S.	Days Exposed	% Loss In T.S.	Fractured Specimens F/N (1)	Fractured Specimens Type(2) Failure	Fractured Specimens Days to Failure	Unfractured Specimens Days Exposed	Unfractured Specimens % Loss In T.S.	Days Exposed	% Loss In T.S.
		Stressed 20 ksi							Stressed 8 ksi						
2024-T351	Method 823	5/5	SCC	2,2,28,31,33	-----	---	-----	---	3/5	SCC	40,49,54	2 @ 55	84	-----	---
	10/110 Cycle	5/5	SCC	1,1,2,2,2	-----	---	-----	---	4/5	SCC	2,18,18,18	1 @ 18	47	-----	---
	Tapwater	4/5	SCC	2,2,2,2,2	1 @ 2	---	-----	---	5/5	SCC	5,35,75,75,75	-----	---	-----	---
	0.008% Benzo.	5/5	SCC	4,7,7,7,7	-----	---	-----	---	1/5	SCC	26	4 @ 90	47	-----	---
	Ocean Water	5/5	SCC	1,1,1,1,1	-----	---	-----	---	3/5	SCC	2,2,4	2 @ 4	19	-----	---
5456-Sens.	Method 823	5/5	SCC	1,1,1,1,1	-----	---	-----	---	5/5	SCC	1,1,1,1,1	-----	---	-----	---
	10/110 Cycle	5/5	SCC	1,1,1,1,1	-----	---	-----	---	3/5	SCC	1,1,1	2 @ 1	20	-----	---
	Tapwater	5/5	SCC	2,2,2,2,2	-----	---	-----	---	5/5	SCC	2,2,2,2,2	-----	---	-----	---
	0.008% Benzo.	5/5	SCC	1,1,1,1,2	-----	---	-----	---	3/5	SCC	4,4,6	2 @ 6	55	-----	---
	Ocean Water	5/5	SCC	1,1,1,1,1	-----	---	-----	---	4/5	SCC	1,1,1,1	1 @ 1	70	-----	---
7079-T651	Method 823	4/5	SCC	3,3,5,5	1 @ 5	---	-----	---	4/5	SCC	54,82,82,90	1 @ 90	---	-----	---
	10/110 Cycle	5/5	SCC	3,3,4,5,5	-----	---	-----	---	0/5	(4)	-------	5 @ 90	52	-----	---
	Tapwater	3/5	SCC	3,3,3	2 @ 3	0	-----	---	3/5	SCC	3,11,16	2 @ 16	4	-----	---
	0.008% Benzo.	4/5	SCC	7,13,14,15	1 @ 15	0	-----	---	2/5	SCC	24,33	3 @ 90	28	-----	---
	Ocean Water	3/5	S.C	4,5,6	2 @ 6	7	-----	---	0/5	(3)	-------	5 @ 90	21	-----	---
7075-T651	Method 823	5/5	SCC	12,12,90,90,90	-----	---	-----	---	2/5	SCC	89,90	3 @ 90	91	-----	---
	10/110 Cycle	5/5	SCC	3,3,3,3,5	-----	---	-----	---	3/5	SCC	3,3,5	2 @ 5	19	-----	---
	Tapwater	5/5	SCC	2,2,2,2,2	-----	---	-----	---	4/5	SCC	4,21,35,35	1 @ 35	---	-----	---
	0.008% Benzo.	3/5	SCC	5,5,6	2 @ 6	2	-----	---	2/5	SCC	45,90	3 @ 90	36	-----	---
	Ocean Water	5/5	SCC	2,2,2,2,2	-----	---	-----	---	3/5	SCC	1,6,10	2 @ 10	6	-----	---
		Stressed 90% Y.S.							Stressed 75% Y.S.						
2024-T851	Method 823	o/11	SCC	5,5,5,8,9,11	4 @ 5	22	1 @ 11	43	6/11	SCC	11,11,13,14,16,16	4 @ 11	37	1 @ 16	50
	10/110 Cycle	5/11	SCC	7,10,11,11,11	4 @ 7	17	2 @ 11	23	4/11	SCC	16,16,18,18	4 @ 16	27	3 @ 18	36
	Tapwater	3/11	SCC	7,10,11	4 @ 7	17	4 @ 11	35	5/11	SCC	10,15,21,21,21	4 @ 10	20	2 @ 21	20
	0.008% Benzo.	3/11	SCC	6,6,24	4 @ 6	10	4 @ 24	22	4/11	SCC	12,42,73,73	4 @ 12	11	3 @ 73	27
	Ocean Water	2/11	SCC	3,9	4 @ 3	8	5 @ 90	6	0/11	(3)	-------	11 @ 90	18	-----	---
7075-T7351	Method 823	3/11	TG	45,47,56	4 @ 45	30	4 @ 56	31	4/11	TG	61,72,73,90	7 @ 90	53	-----	---
	10/110 Cycle	4/11	TG	45,45,49,56	3 @ 48	37	4 @ 56	47	5/11	TG	47,54,82,83,83	4 @ 54	29	2 @ 83	47
	Tapwater	6/11	TG	51,59,75,79,84,85	4 @ 51	37	1 @ 85	45	2/11	TG	75,77	4 @ 77	44	4 @ 90	35
	0.008% Benzo.	0/11	(5)	-------	11 @ 90	26	-----	---	0/11	(5)	-------	11 @ 90	15	-----	---
	Ocean Water	0/11	(3)	-------	11 @ 90	1	-----	---	0/11	(3)	-------	11 @ 90	1	-----	---
7.XX-T7351	Method 823	4/11	TG	16,16,17,17	4 @ 16	42	3 @ 17	36	6/11	TG	20,21,21,29,29,31	3 @ 21	44	2 @ 31	44
	10/110 Cycle	4/11	TG	16,18,20,21	4 @ 16	32	3 @ 20	42	5/11	TG	22,24,25,27,27	4 @ 22	33	2 @ 27	33
	Tapwater	4/11	TG	21,21,30,30	4 @ 21	27	3 @ 30	37	4/11	TG	14,23,25,25	4 @ 14	18	3 @ 25	40
	0.008% Benzo.	3/11	TG	13,19,19	4 @ 13	24	4 @ 19	26	4/11	TG	19,22,24,24	3 @ 19	37	4 @ 24	27
	Ocean Water	0/11	(5)	-------	11 @ 90	15	-----	---	0/11	(5)	-------	11 @ 90	6	-----	---

NOTES: (1) Number of Failures/Number of Specimens Exposed.
(2) SCC = Intergranular cracks typical of SCC.
TG = Transgranular cracks not typical of SCC.
(3) Metallographic examination did not show any incipient cracking for unfailed specimens exposed 90 days.
(4) Metallographic examination showed short intergranular SCC in unfailed specimens exposed 90 days.
(5) Metallographic examination showed small transgranular cracks in unfailed specimens exposed 90 days.
(6) Metallographic examination of failed specimens showed mixed mode cracking.

Table IV

EFFECT OF SPECIMEN SIZE AND STIFFNESS OF STRESSING FRAME ON SHORT-TRANSVERSE RESISTANCE TO SCC
ENVIRONMENT: 3.5% NaCl-ALTERNATE IMMERSION WITH SOLUTION PURITY AND AIR CONDITIONS
PER FEDERAL METHOD 823 - SOLUTION CHANGED MONTHLY

			Fractured Specimens			Unfractured Specimens				Fractured Specimens			Unfractured Specimens			
Alloy	Specimen Dia. In.(1)	Frame Size(1)	F/N (2)	Type(3) Failure	Days to Failure	Days Exposed	% Loss In T.S.	Days Exposed	% Loss In T.S.	F/N (2)	Type(3) Failure	Days to Failure	Days Exposed	% Loss In T.S.	Days Exposed	% Loss In T.S.
			Stressed 20 ksi							Stressed 8 ksi						
2024-T351	1/8	A	5/5	SCC	2,2,28,31,33	-----	---	-----	---	3/5	SCC	40,49,54	2 @ 55	84	-----	---
	1/8	B	3/5	SCC	2,2,2	2 @ 2	82	-----	---	5/5	SCC	29,29,29,29,29	-----	---	-----	---
	1/4	B	5/5	SCC	14,14,16,16,16	-----	---	-----	---	4/5	SCC	73,90,90,90	1 @ 90	---	-----	---
7075-T651	1/8	A	5/5	SCC	12,12,90,90,90	-----	---	-----	---	2/5	SCC	89,90	3 @ 90	91	-----	---
	1/8	B	5/5	SCC	2,2,2,2,2	-----	---	-----	---	3/5	SCC	37,45,64	2 @ 64	74	-----	---
	1/4	B	4/5	SCC	4,6,11,11	1 @ 11	---	-----	---	0/5	(4)	----------	5 @ 90	77	-----	---
			Stressed 90% Y.S.							Stressed 75% Y.S.						
2024-T851	1/8	A	6/11	SCC	5,5,5,8,9,11	4 @ 5	22	1 @ 11	43	6/11	SCC	11,11,13,14,16,16	4 @ 11	37	1 @ 16	50
	1/8	B	4/11	SCC	2,3,6,6	4 @ 2	12	3 @ 6	23	5/11	SCC	9,9,10,10,10	3 @ 9	33	3 @ 10	33
	1/4	B	4/11	SCC	14,14,14,19	4 @ 14	9	3 @ 19	16	3/11	SCC	17,41,41	4 @ 17	19	4 @ 41	19
7075-T7351	1/8	A	3/11	TG	45,47,56	4 @ 45	30	4 @ 56	31	4/11	TG	61,72,73,90	7 @ 90	43	-----	---
	1/8	B	4/11	TG	42,45,46,48	4 @ 45	47	3 @ 48	37	3/11	TG	68,89,90	4 @ 66	48	4 @ 90	36
	1/4	B	0/11	(5)	----------	11 @ 90	21	-----	---	0/11	(5)	----------	11 @ 90	18	-----	---
7XXX-T7351	1/8	A	4/11	TG	16,16,17,17	4 @ 16	42	3 @ 17	36	6/11	TG	20,21,21,29,29,31	3 @ 21	44	2 @ 31	44
	1/8	B	5/11	TG	18,18,20,20,20	4 @ 18	32	2 @ 20	35	5/11	TG	29,27,27,28,34	4 @ 27	41	2 @ 34	54
	1/4	B	3/11	TG	25,25,64	4 @ 25	22	4 @ 64	33	4/11	TG	53,82,90,90	4 @ 53	27	3 @ 90	53

NOTES:
(1) Dimensions of specimens and stressing frame shown in Figure 1.
(2) Number of Failures/Number of Specimens Exposed.
(3) SCC = Intergranular cracks typical of SCC.
TG = Transgranular cracks not typical of SCC.
(4) Metallographic examination showed short intergranular SCC.
(5) Metallographic examination showed small transgranular cracks emanating from pits.

Table V

INDEPENDENT TESTS BY ALCOA COMPARING RESULTS OF SHORT-TRANSVERSE SCC TESTS OF 2-IN. PLATE IN THE ALTERNATE IMMERSION AND BOILING SALT TESTS WITH THOSE FROM SEACOAST ATMOSPHERE AT POINT JUDITH, R. I. AND INLAND INDUSTRIAL ATMOSPHERE AT NEW KENSINGTON, PA.

				Days to Failure(1)			
Alloy	S. No.	Y.S. ksi	Applied Stress, ksi	3.5% NaCl Alt. Imm.(2)	Boiling 6% NaCl Soln.	Seacoast Atmos.	Industrial Atmos.
7075-T651	366683	67.3	26	26	2	41	410
			18	OK 84	3	499	458
			7	OK 84	OK 4	OK 561	OK 1500
7XXX-T7351 (X7375 + Ag + Zr)	366688	60.8	50	54*	4	408**	1167
			46	54*	4	499**	1277
			42	54*	1	OK 561	OK 1771
			38	OK 84	OK 4	OK 561	OK 1771
7075-T7351	366684	54.3	50	OK 84	OK 4	OK 561	OK 1771
			46	OK 84	OK 4	OK 561	OK 1771

NOTES:
(1) Individual specimens tested at each of the specified stress levels.
(2) Salt solution made with commercial grade NaCl and New Kensington tapwater.
* Failure was associated with transgranular cracking not typical of SCC.
** Failure associated with both intergranular and transgranular cracking.

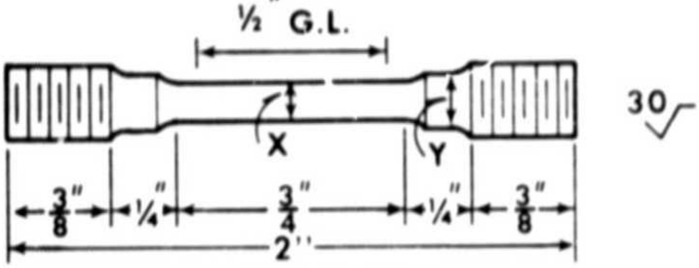
Table VI

RESULTS OF TRANSVERSE SCC TESTS OF 7075-T7351 ROLLED 2-1/2-IN. DIAMETER ROD[11]
STRESS: 44 ksi (75% Trans. Y.S.)

Type of Specimen	Test Environment	F/N	Days To Failure
2.25-In. O.D. x 0.125-in. wall Interference-stressed ring	3.5% NaCl Alternate Immersion - Lab A	5/5*	446 - 553
2.25-In. O.D. x 0.125-in. wall Interference-stressed ring	Seacoast Atmos., Pt. Comfort, Texas	0/5	OK 8 years
0.125-in. tensile specimen - Frame A	3.5% NaCl Alternate Immersion - Lab A	0/5	OK 84
0.125-in. tensile specimen - Frame A	3.5% NaCl Alternate Immersion - Lab B (Mthd. 823)	0/5	OK 84
0.125-in. tensile specimen - Frame A	3.5% NaCl Alternate Immersion - Lab C (Mthd. 823)	5/5*	50,56,64,71,88
0.125-in. tensile specimen - Frame A	3.5% NaCl Alternate Immersion - Lab D	0/5	OK 84
0.125-in. tensile specimen - Frame A	Seacoast Atmos., Pt. Comfort, Texas	0/5	OK 8 years
0.125-in. tensile specimen - Frame A	Seacoast Atmos., Pt. Judith, R.I.	0/5	OK 8 years
0.125-in. tensile specimen - Frame A	Industrial Atmos., New Kensington, Pa.	0/5	1 OK 4 years**, 4 OK 8 years

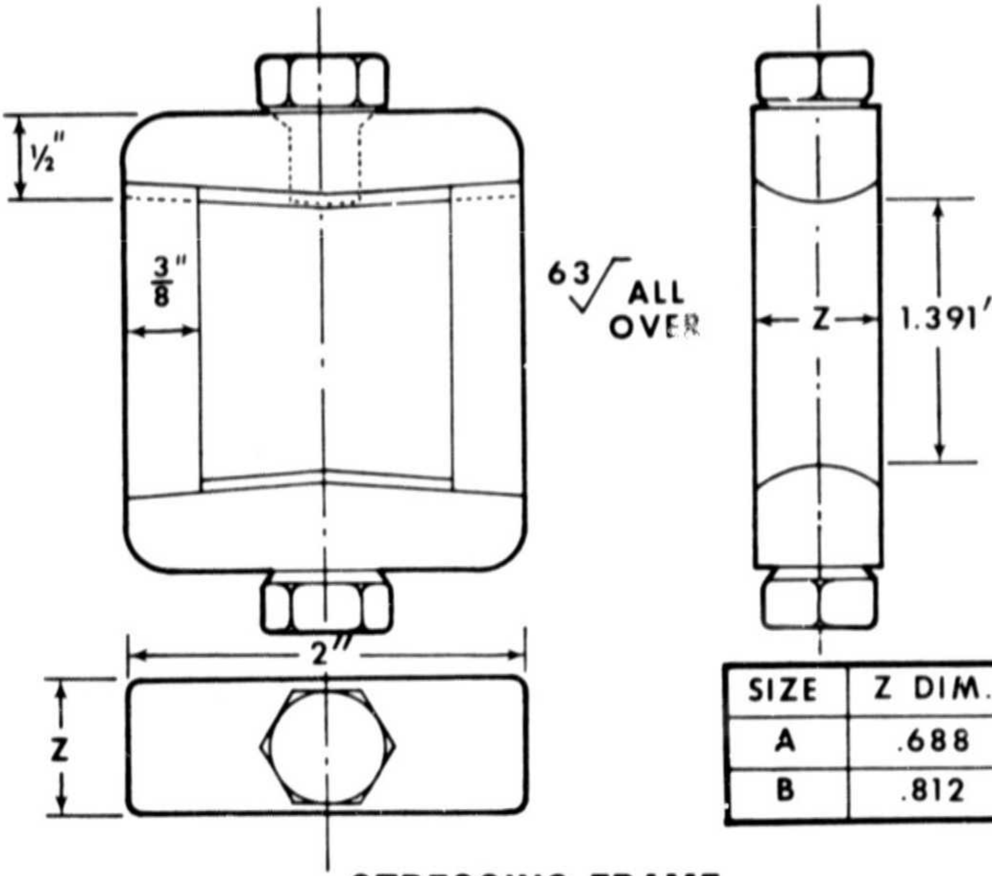
*Fractures associated with severe pitting and transgranular cracks established by metallographic and fractographic examinations to be mechanical failures.

**Removed from test for metallographic examination which verified absence of any cracking.



ROUND TENSILE SPECIMEN

X DIA.	Y DIA.	THD. SIZE
.125	.156	¼ -20
.250	.281	3/8 -16



SIZE	Z DIM.
A	.688
B	.812

STRESSING FRAME

FIGURE 1 SKETCH SHOWING PRINCIPAL DIMENSIONS OF THE TWO SIZES OF TENSILE ROUNDS AND STRESSING FRAMES. MOST OF THE 1/8-IN. SPECIMENS WERE STRESSED IN FRAME A BUT SOME WERE TESTED IN BOTH FRAMES. THE 1/4-IN. SPECIMEN CAN BE STRESSED ONLY IN FRAME B.

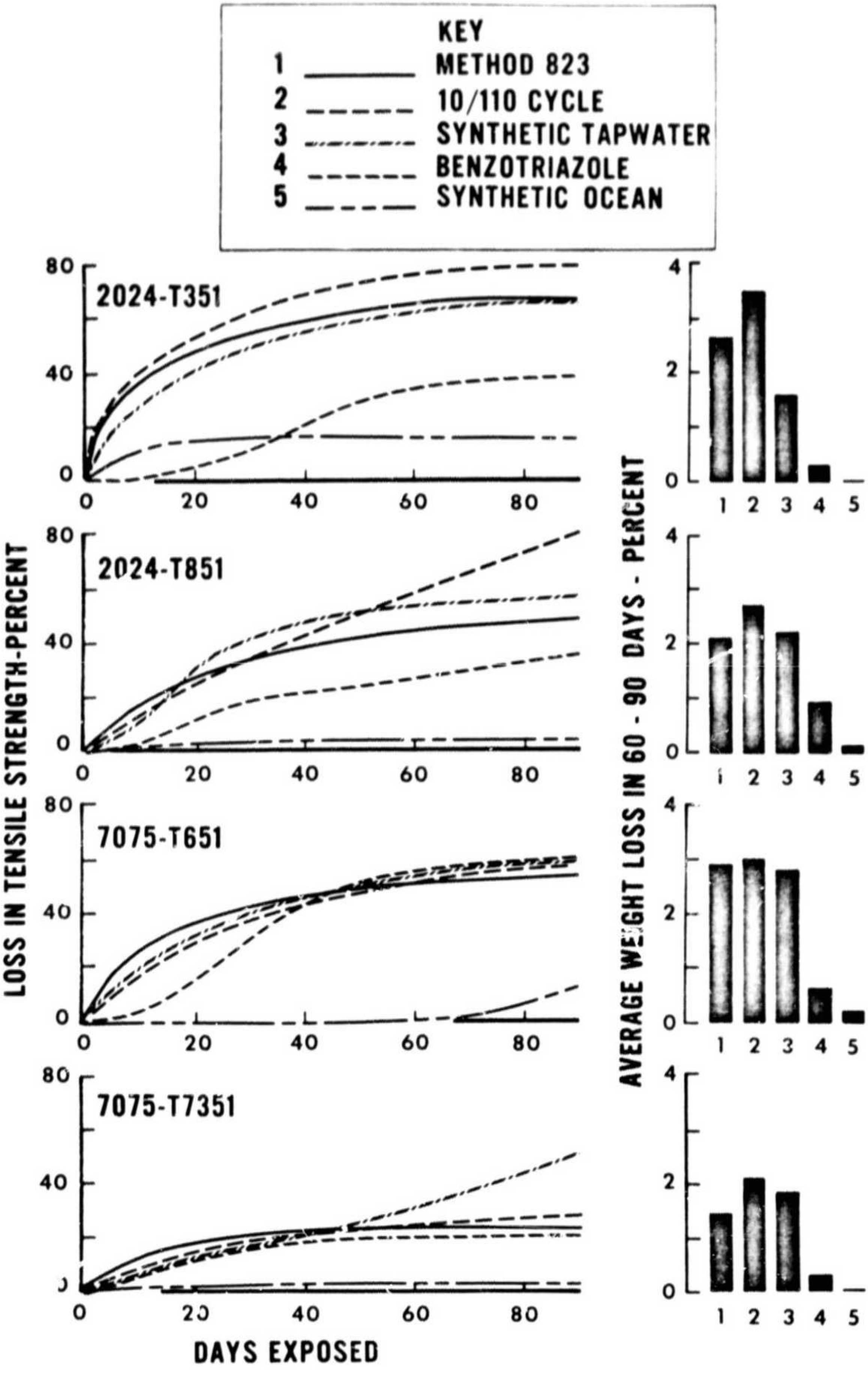


FIGURE 2 RELATIVE CORROSIVENESS OF VARIOUS MODIFICATIONS OF THE 3.5% NaCl ALTERNATE IMMERSION TEST (METHOD 823)

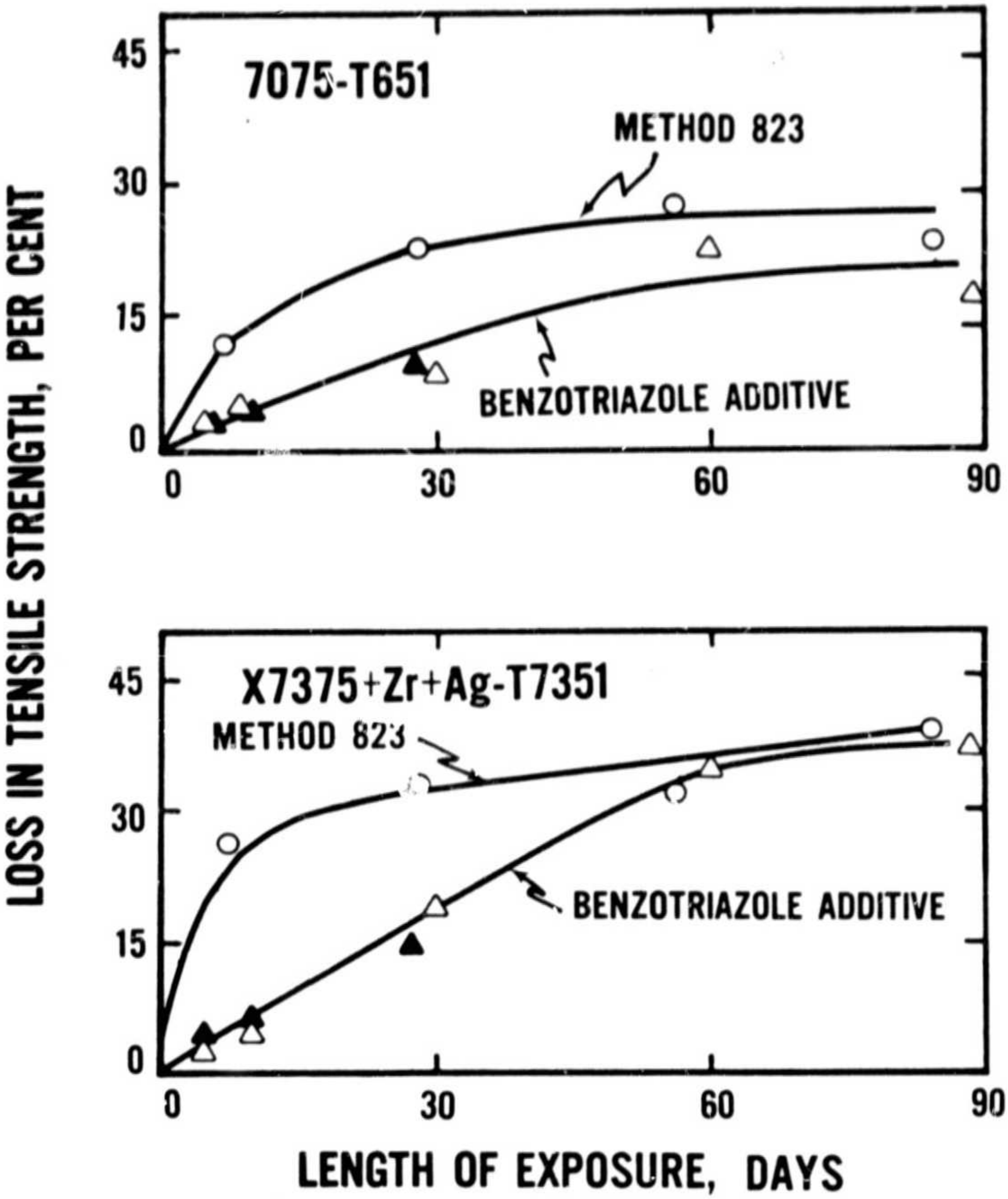


FIGURE 3 INDEPENDENT TESTS OF BENZOTRIAZOLE ADDITIVE SHOWING THAT ITS ABILITY TO RETARD GENERAL CORROSION WAS NOT ENHANCED BY MORE FREQUENT CHANGE OF SOLUTION. THE OPEN-POINT DATA WERE OBTAINED USING MONTHLY SOLUTION CHANGES AND A BENZOTRIAZOLE CONCENTRATION OF 0.008%. THE CLOSED-POINT DATA REPRESENT A WEEKLY SOLUTION CHANGE AND A BENZOTRIAZOLE CONCENTRATION OF 0.01%.

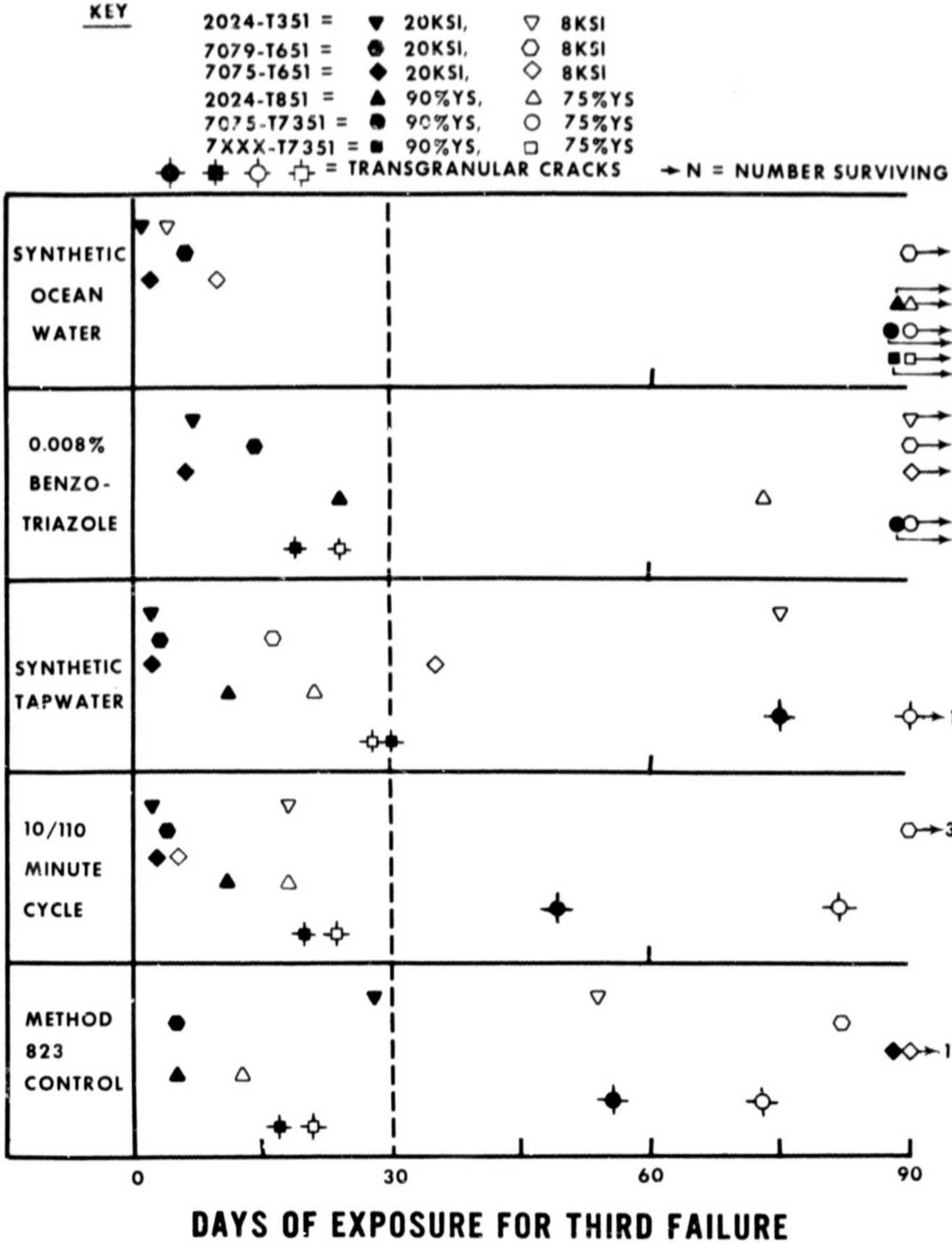


FIGURE 4 RELATIVE SCC PERFORMANCE OF VARIOUS MODIFICATIONS OF THE 3.5% NaCl ALTERNATE IMMERSION TEST (METHOD 823)

	NATURAL ENVIRONMENTS - 4 YEARS		LABORATORY ALTERNATE IMMERSION 90 DAY		
	INLAND INDUSTRIAL ATMOSPHERE	SEACOAST ATMOSPHERE	0.008% BENZOTRIAZOLE	SYNTHETIC OCEAN WATER	METHOD 823 10/110 MIN. CYCLE SYN. TAPWATER
FAILURE BY SCC	7XXX-T7351	2024-T851 7XXX-T7351-	2024-T851		2024-T851
TRANSGRANULAR CRACKING		7XXX-T7351-	7XXX-T7351		7XXX-T7351 7075-T7351
NO FAILURE	7075-T7351 2024-T851	7075-T7351	7075-T7351 **	7075-T7351 2024-T851 7XXX-T7351 **	

NOTES: * A MIXTURE OF INTERGRANULAR AND TRANSGRANULAR CRACKING OCCURRED.
** SHORT TRANSGRANULAR CRACKS DETECTED METALLOGRAPHICALLY.

FIGURE 5 - COMPARISON OF THE FIVE ALTERNATE IMMERSION PROCEDURES WITH PERFORMANCE IN NATURAL ENVIRONMENTS. SHORT - TRANSVERSE SCC SPECIMENS OF THE THREE "HIGH" RESISTANCE ALLOYS AT A TEST STRESS OF 75% Y.S.

S. NO. 366937-N97 NEG. NO. 182841 KELLER'S ETCH MAG. 500 X

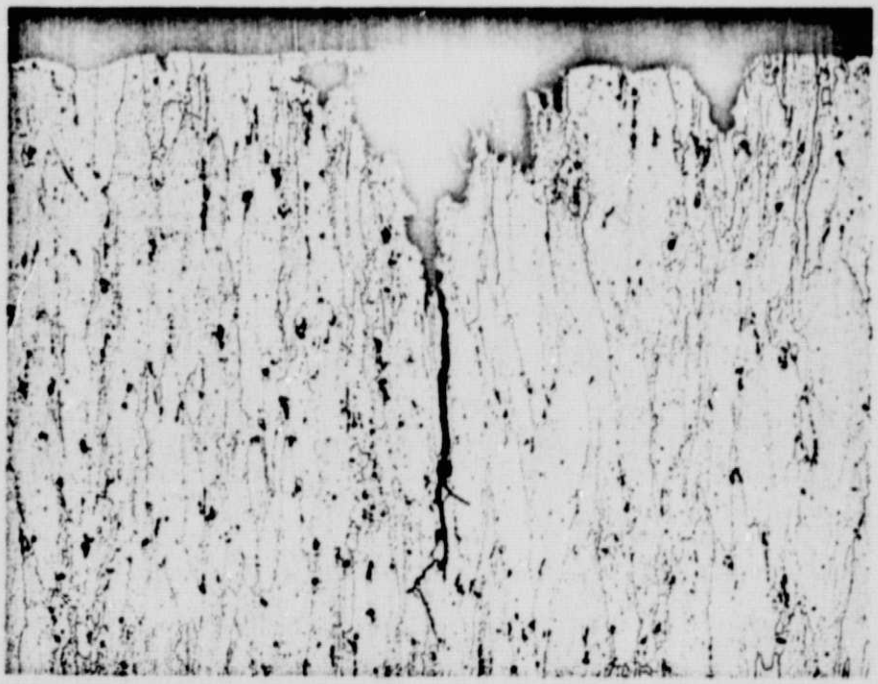
FIGURE 6 - 2024-T851 ALLOY, 1/8-IN. DIA. SPECIMEN IN FRAME A, STRESSED 90% Y.S. FAILED AFTER 5 DAYS EXPOSURE TO HIGH PURITY SALT SOLUTION. NOTE THE SHORT INTERGRANULAR CRACK EMANATING FROM THE PITTING ATTACK. NUMEROUS SUCH CRACKS WERE FOUND IN ALL FAILED 2024-T851 SPECIMENS INDICATING FAILURE BY SCC.

S. NO. 366939-N104 NEG. NO. 182840 KELLER'S ETCH MAG: 500 X

FIGURE 7 - 7075-T7351 ALLOY, 1/8-IN. DIA. SPECIMEN IN FRAME A, STRESSED 90% Y.S., FAILED AFTER 45 DAYS EXPOSURE TO HIGH PURITY SALT SOLUTION. NUMEROUS TRANSGRANULAR CRACKS, SUCH AS THE ONE ILLUSTRATED, WERE FOUND IN ALL 7075-T7351 SPECIMENS EXAMINED WITH NO EVIDENCE WHATSOEVER OF INTERGRANULAR CRACKING. THIS INDICATES THE 7075-T7351 FAILURES WERE NOT TYPICAL INTERGRANULAR STRESS-CORROSION CRACKING

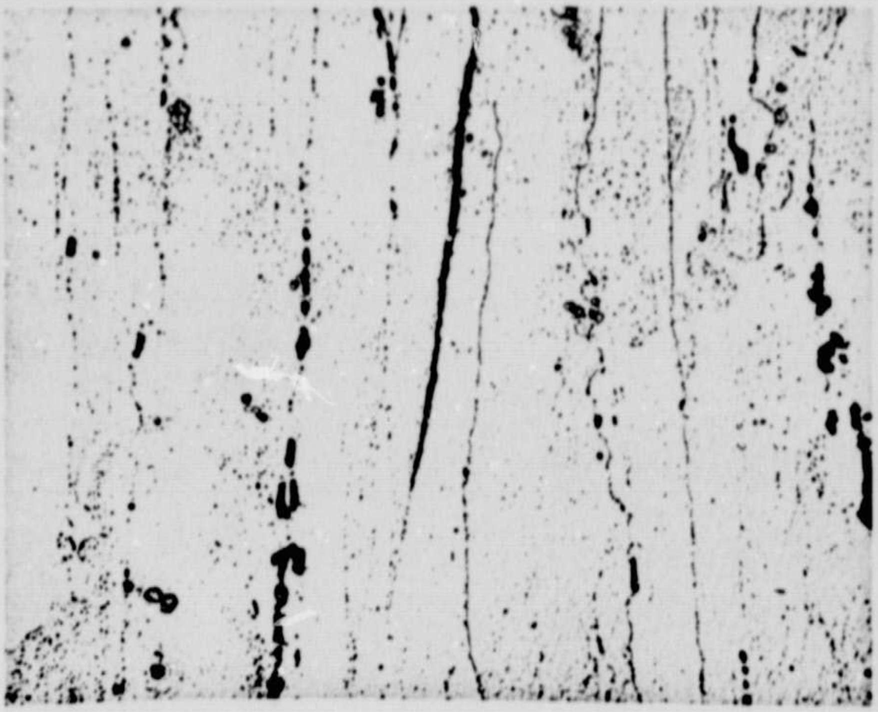
S. NO. 366688-N102   NEG. NO. 182842   KELLER'S ETCH   MAG: 100 X

FIGURE 8 - 7XXX-T7351 ALLOY, 1/8-IN. DIA. SPECIMEN IN FRAME A, STRESSED 90% Y.S. FAILED AFTER 17 DAYS EXPOSURE TO HIGH PURITY SALT SOLUTION. NUMEROUS TRANSGRANULAR CRACKS, AND NO INTERGRANULAR CRACKING WERE DETECTED IN ALL 7XXX-T7351 SPECIMENS EXAMINED.



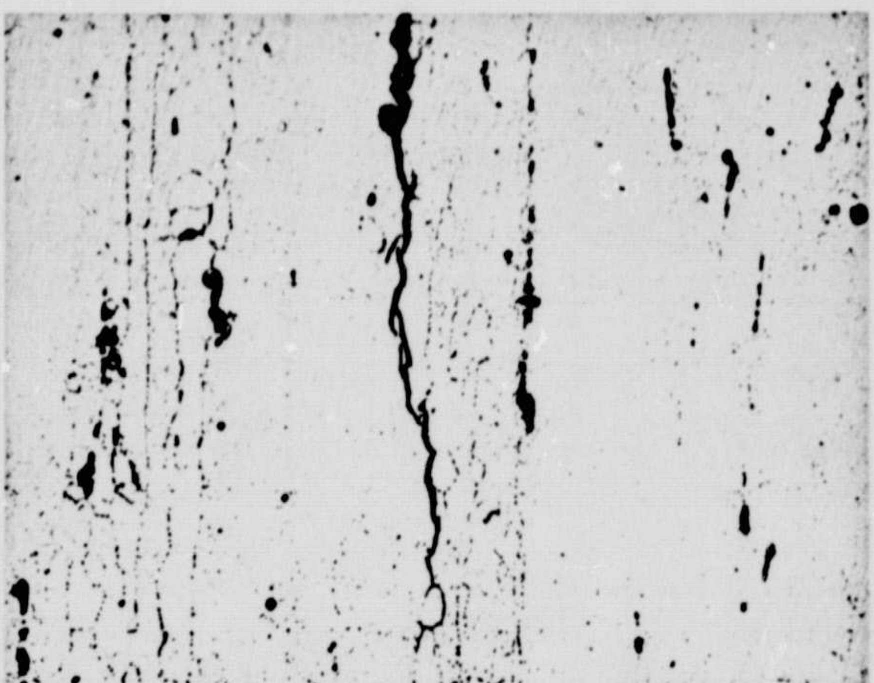
S. NO. 366688-N41S   NEG. NO. 182845   KELLER'S ETCH   MAG: 100 X

FIGURE 9 - 7XXX-T7351 ALLOY, 1/4-IN. DIA SPECIMEN IN FRAME B, STRESSED 75% Y.S. FAILED AFTER 53 DAYS EXPOSURE TO HIGH PURITY SALT SOLUTION. SHOWS THAT THE TRANSGRANULAR CRACKING OCCURRED EVEN WITH THE LARGER SPECIMEN.



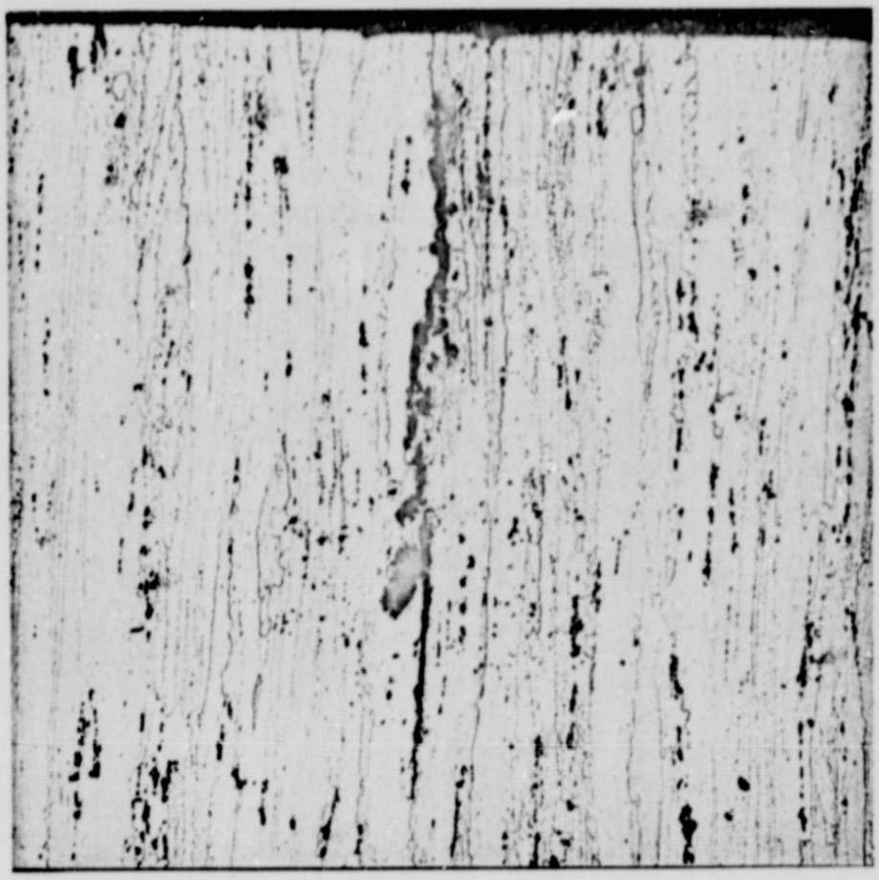
S. NO. 343149-11-N14 NEG. NO. 183886 KELLER'S ETCH MAG: 500 X

FIGURE 10 - AN AUXILIARY SCC CRACK IN A 7XXX-T7351 SPECIMEN THAT FAILED AFTER 1156 DAYS EXPOSURE TO INDUSTRIAL ATMOSPHERE AT A STRESS OF 34 KSI ALL THE 7XXX-T7351 SPECIMENS THAT FAILED IN THIS ENVIRONMENT SHOWED TYPICAL SCC CRACKS OF THIS SORT



S. NO. 366688-N227 NEG. NO. 183582 KELLER'S ETCH MAG: 500 X

FIGURE 11 - AN AUXILIARY CRACK IN A 7XXX-T7351 SPECIMEN THAT FAILED AFTER 408 DAYS EXPOSURE TO SEACOAST ATMOSPHERE AT A STRESS OF 50 KSI. AT LEAST THE LEADING PORTION OF THE CRACK IS INTERGRANULAR AND TYPICAL OF SCC. SOME OF THE OTHER AUXILIARY CRACKS IN THIS AND OTHER SEACOAST ATMOSPHERE FRACTURED SPECIMENS WERE TRANSGRANULAR



S. NO. 366688-N283 NEG. NO. 180131A KELLER'S ETCH MAG: 100 X

FIGURE 12 - AN AUXILIARY CRACK PARALLEL TO THE MAIN FRACTURE IN A 7XXX-T7351 SPECIMEN THAT FAILED AFTER 4 DAYS EXPOSURE TO BOILING 6% NaCl SOLUTION AT A STRESS OF 46 KSI. THE CRACK IS REPRESENTATIVE OF THE AUXILIARY CRACKS IN THIS AND OTHER 7XXX-T7351 SPECIMENS THAT FAILED IN THIS ENVIRONMENT AND IS CONSIDERED TO BE THE RESULT OF STRESS-CORROSION CRACKING. NOTE THE ABSENCE OF ANY APPRECIABLE PITTING CORROSION OF SURFACE IN THIS ENVIRONMENT COMPARED WITH THAT WHICH OCCURRED IN THE 3.5% NaCl ALTERNATE IMMERSION TEST, SEE FIGURES 8 AND 9.

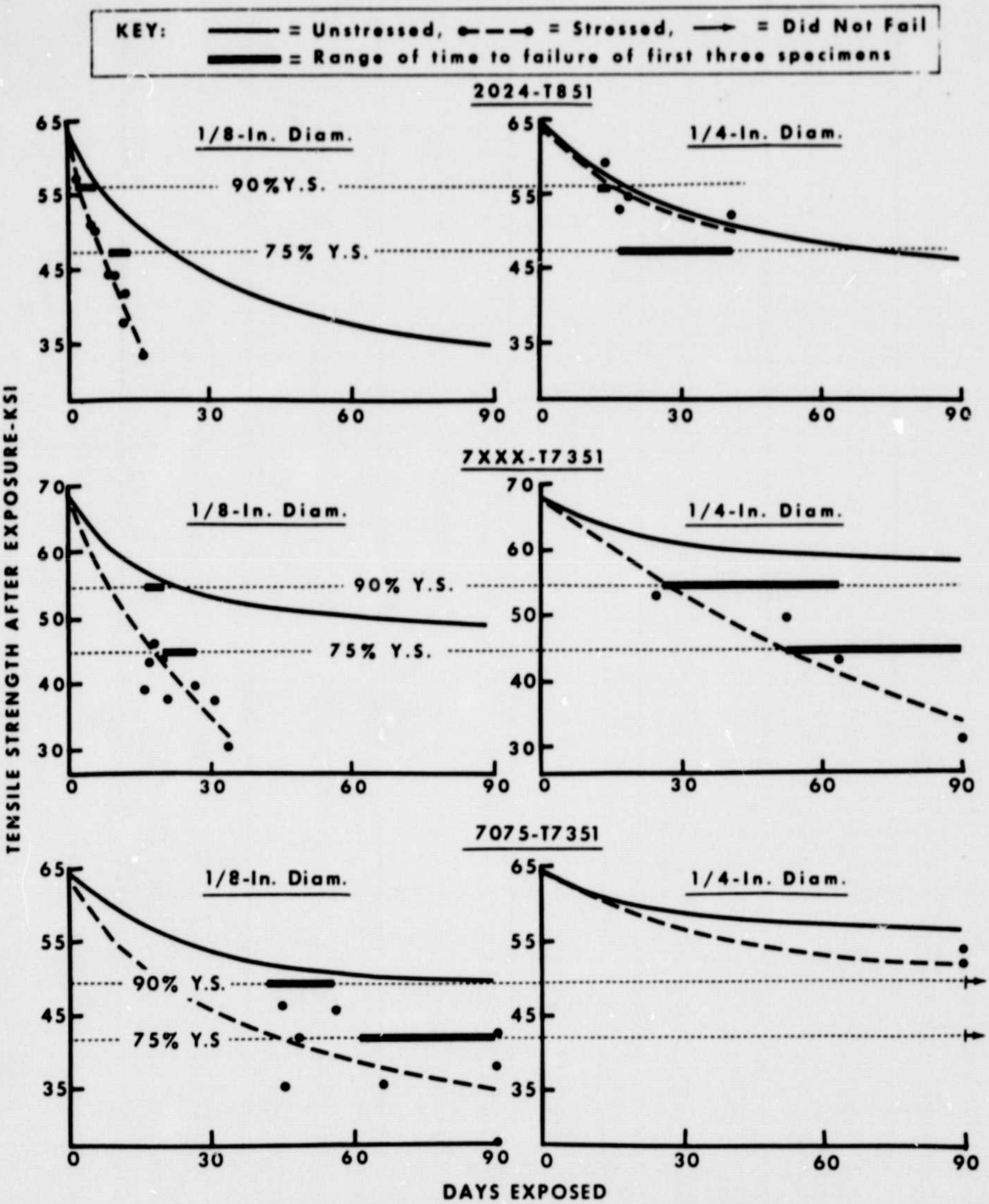
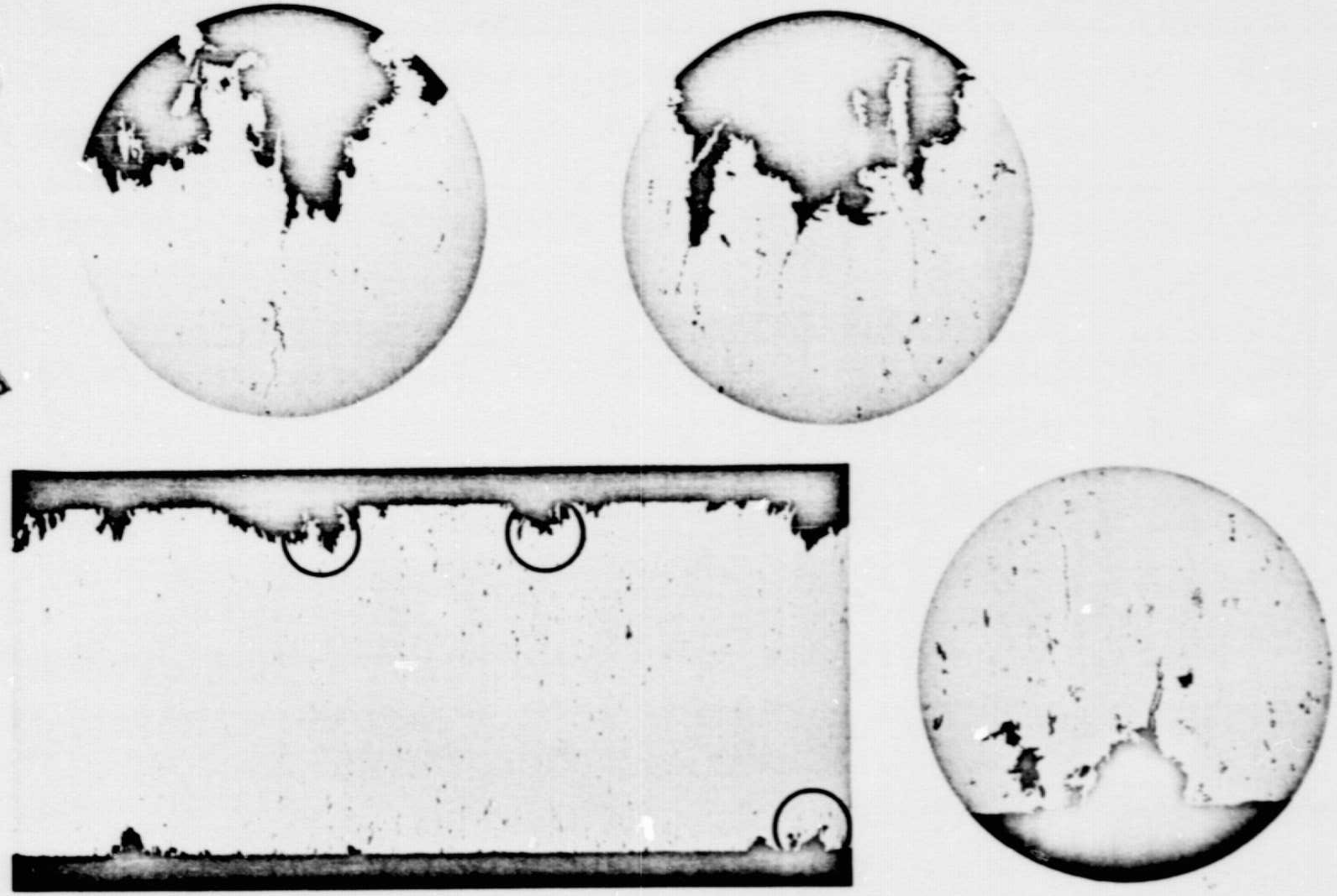


FIGURE 13 COMPARISON OF LOSS IN STRENGTH FROM CORROSION OF UNSTRESSED AND STRESSED SPECIMENS EXPOSED TO 3.5% NaCl-A.I. PER METHOD 823



NEG. NO. 7207068

AS POLISHED, MAGNIFICATIONS 20 AND 100X

FIGURE 14 - SECTION (20X) THROUGH THE GAGE LENGTH OF AN 1/8-IN. 7075-T7351 SPECIMEN CORRODED UNDER STRESS, REMOVED PRIOR TO FAILURE AND THE THEN TENSILE TESTED. NUMEROUS SHORT, TRANSGRANULAR CRACKS EMANATED FROM SITES OF PITTING CORROSION (AS ILLUSTRATED BY THE THREE 100X INSERTS) THAT DRASTICALLY REDUCED THE FINAL BREAKING STRENGTH. THIS SAME SITUATION EXISTED IN THE 7XXX-T7351 AND 2024-T851 SPECIMENS, EXCEPT CRACKING IN LATTER ALLOY WAS INTERGRANULAR.

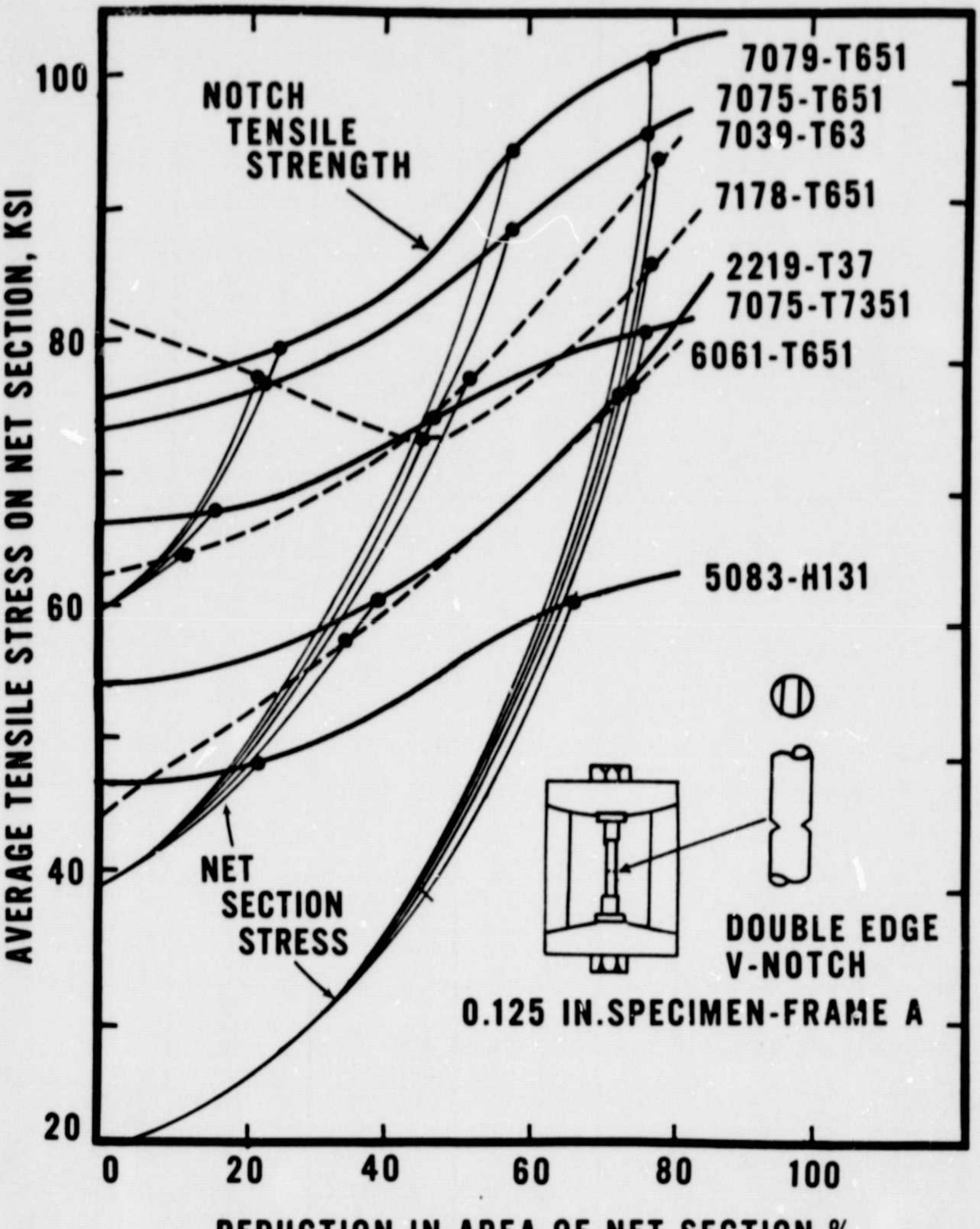


FIGURE 15 EFFECT OF INCREASING DEPTH OF NOTCH ON NOTCH TENSILE STRENGTH AND ON NET SECTION STRESS OF 0.125-IN. SPECIMENS STRESSED IN FRAME A

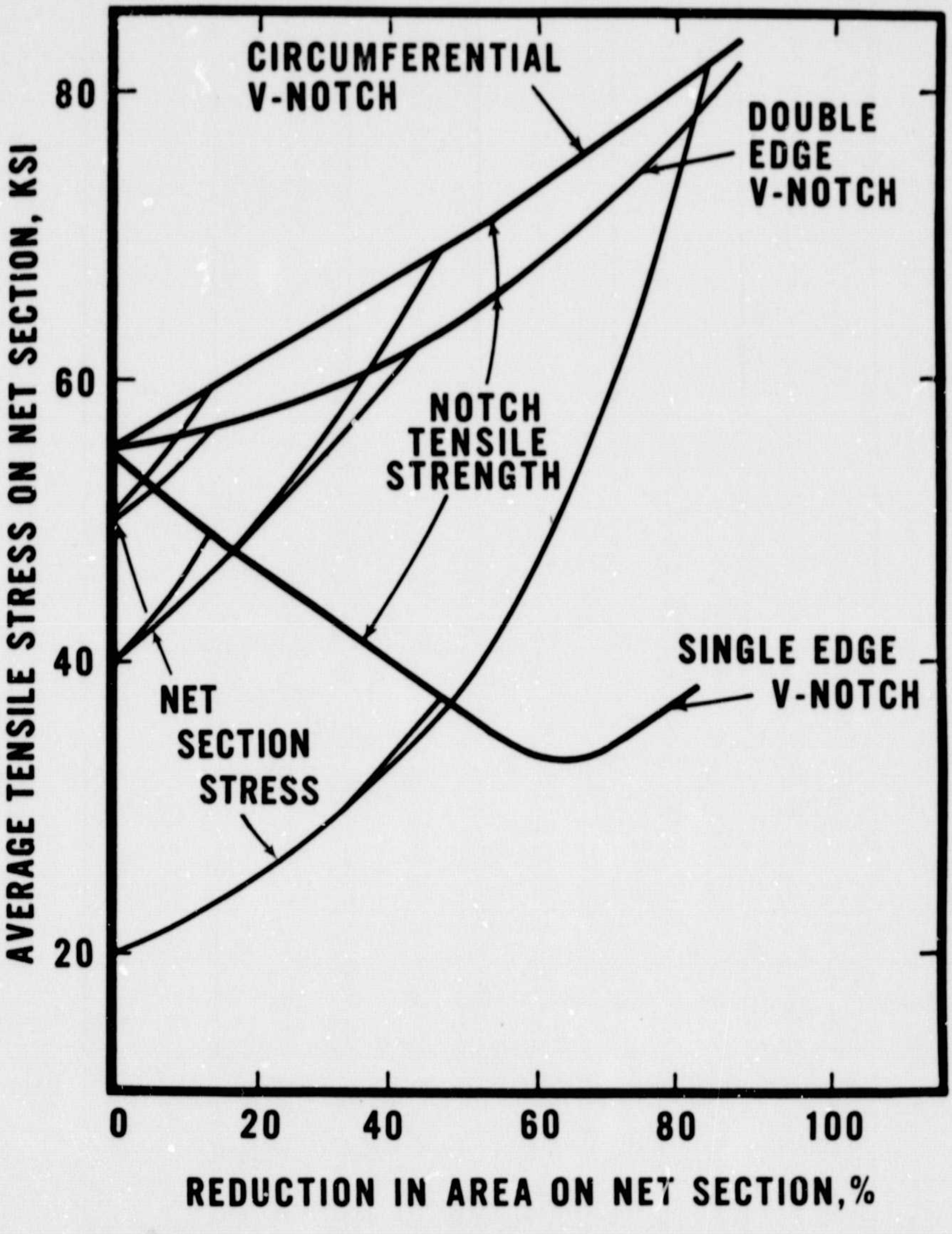


FIGURE 16 EFFECT OF TYPE OF SIMULATED CRACK ON NOTCH TENSILE STRENGTH AND ON NET SECTION STRESS OF 0.125-IN. DIA. 2219-T37 SPECIMENS IN FRAME A

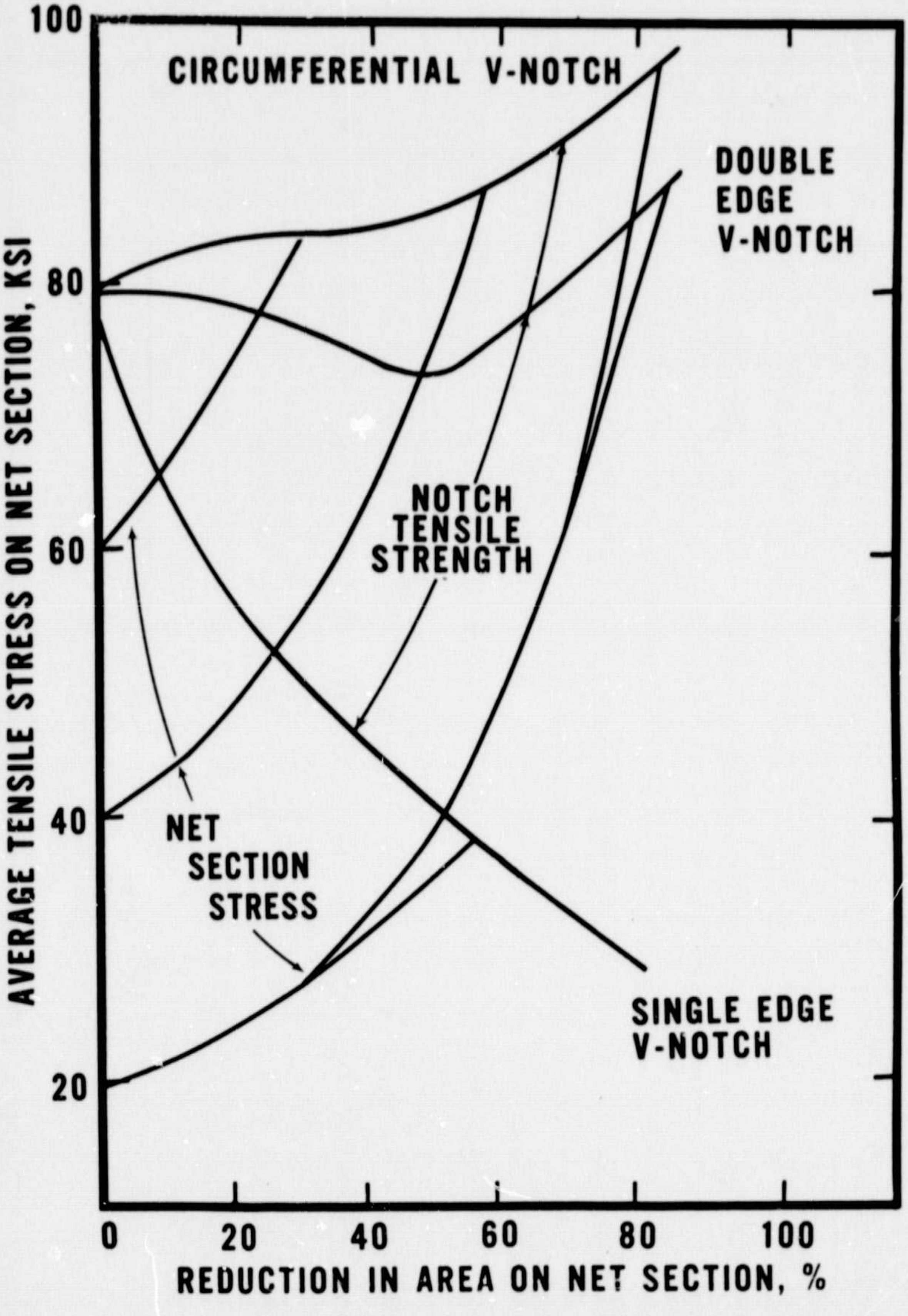


FIGURE 17 EFFECT OF TYPE OF SIMULATED CRACK ON NOTCH TENSILE STRENGTH AND ON NET SECTION STRESS OF 0.125 IN. DIA. 7178-T651 SPECIMENS IN FRAME A

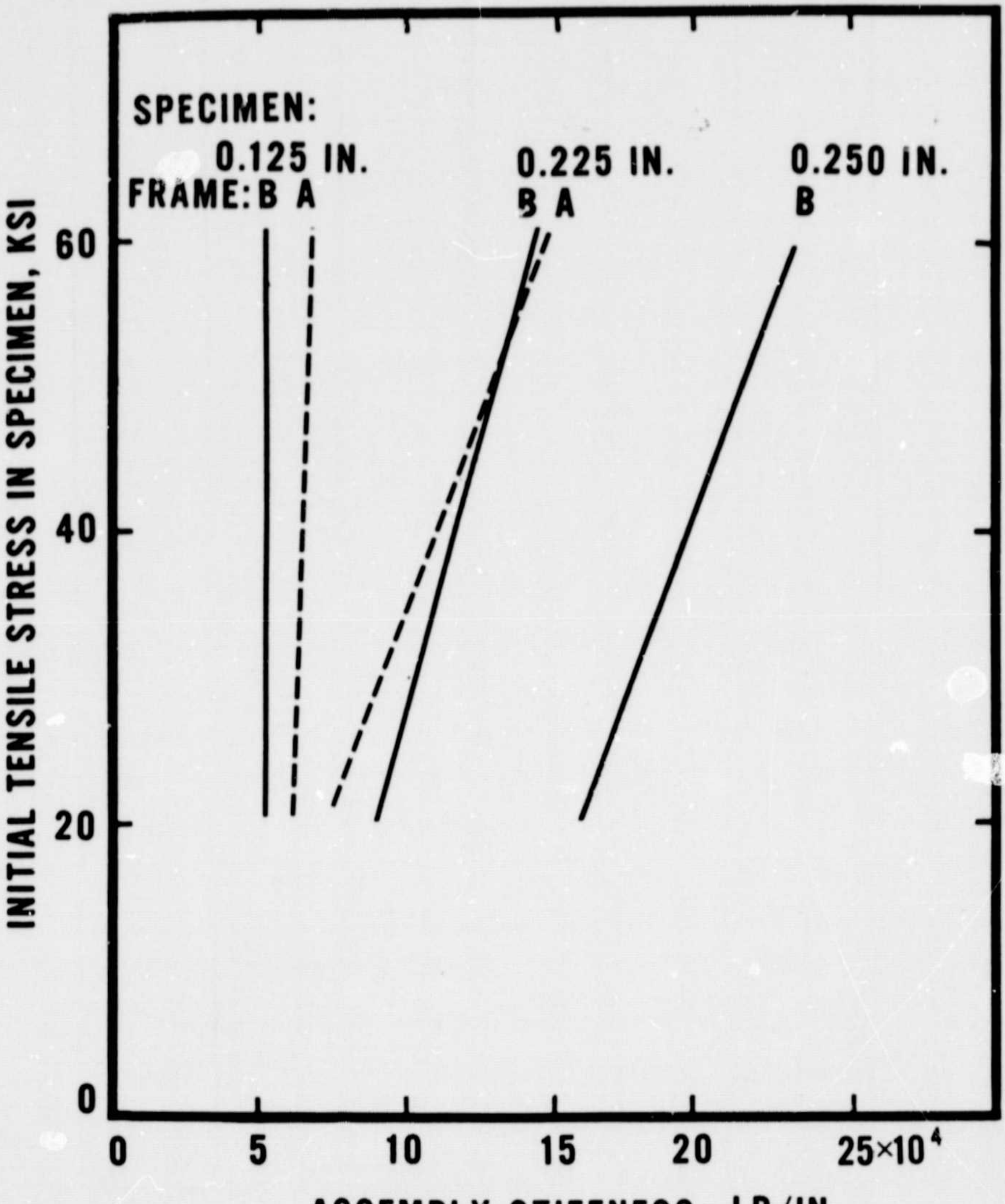


FIGURE 18 STIFFNESS OF VARIOUS SPECIMEN FRAME ASSEMBLIES

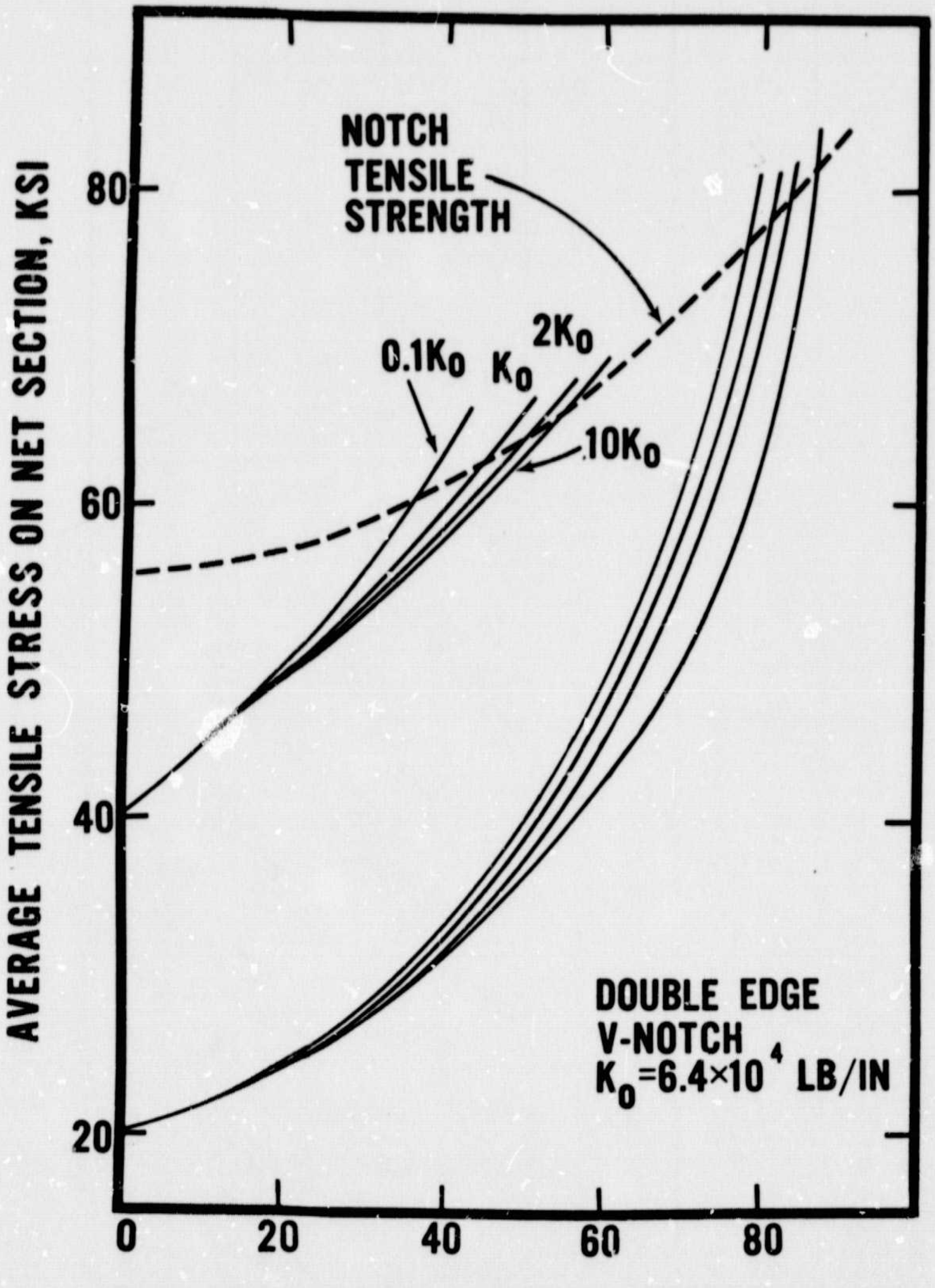


FIGURE 19 EFFECT OF SPECIMEN-FRAME ASSEMBLY STIFFNESS ON NET SECTION STRESS IN 0.125 IN. DIA. SPECIMENS OF 2219-T37 ALLOY

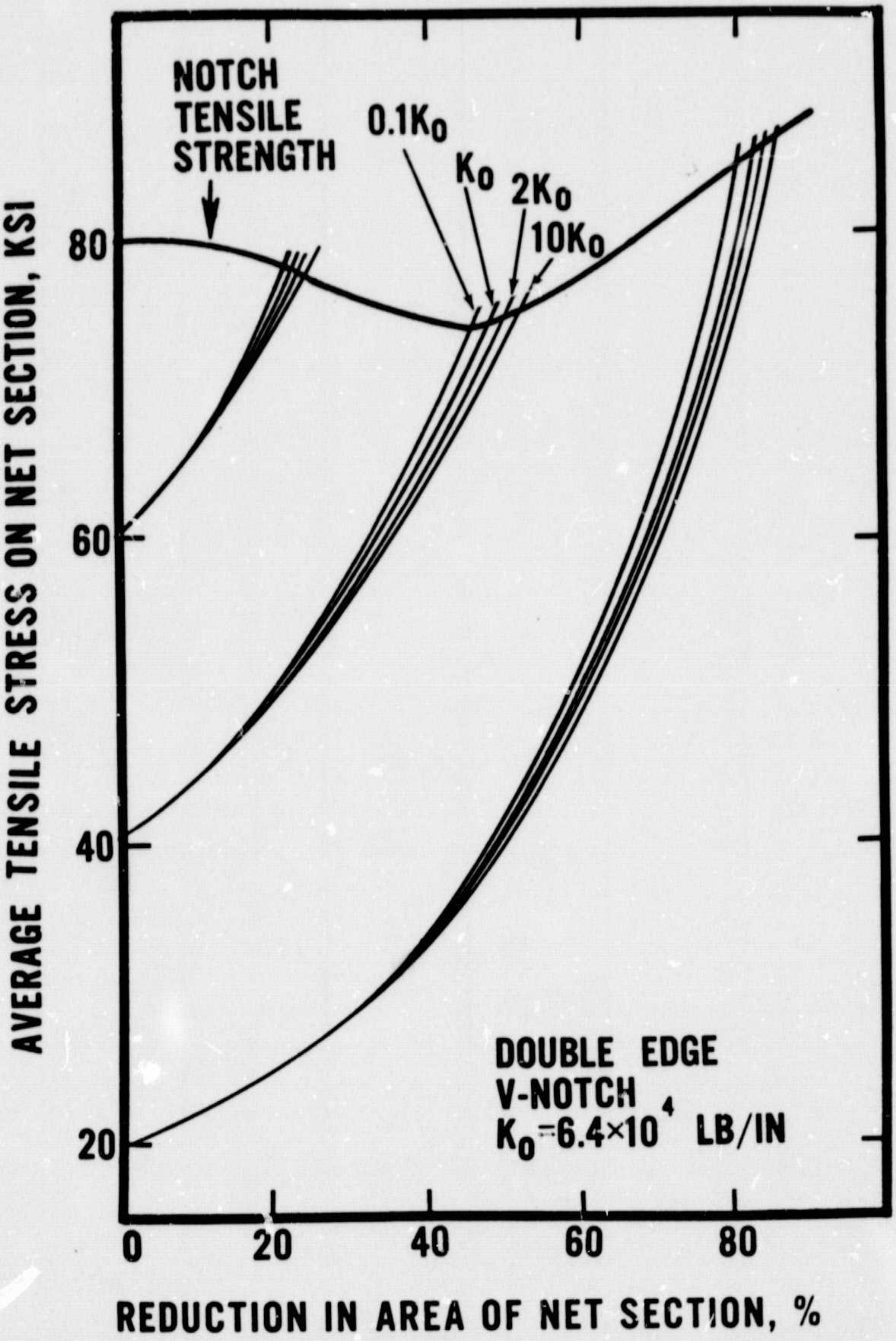


FIGURE 20 EFFECT OF SPECIMEN-FRAME ASSEMBLY STIFFNESS ON NET SECTION STRESS IN 0.125 IN. DIA. SPECIMENS OF 7178-T651 ALLOY

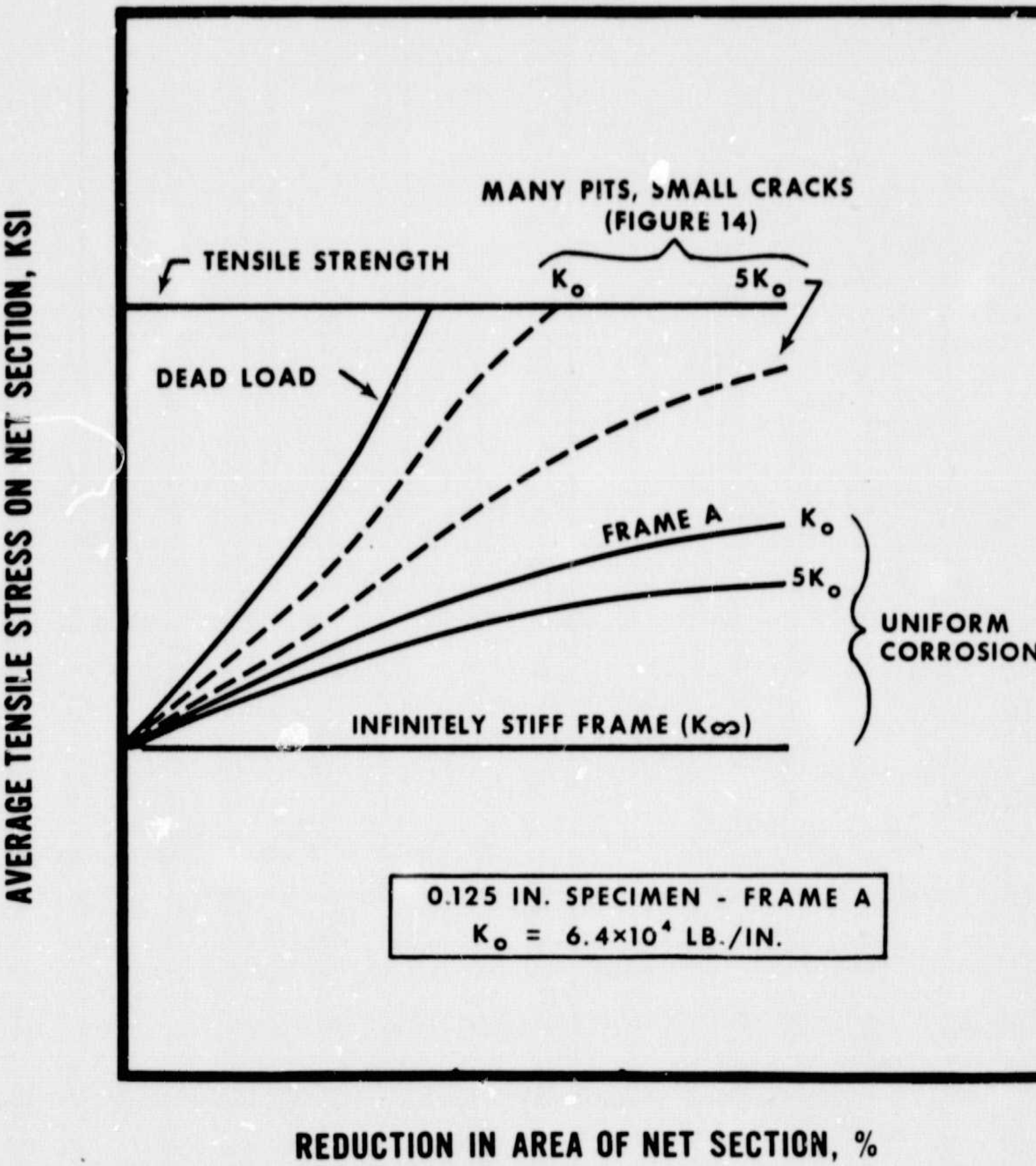


FIGURE 21 EFFECT OF CORROSION PATTERN AND SPECIMEN-FRAME STIFFNESS ON NET SECTION STRESS IN 0.125-IN. SPECIMEN OF 7075-T7351.

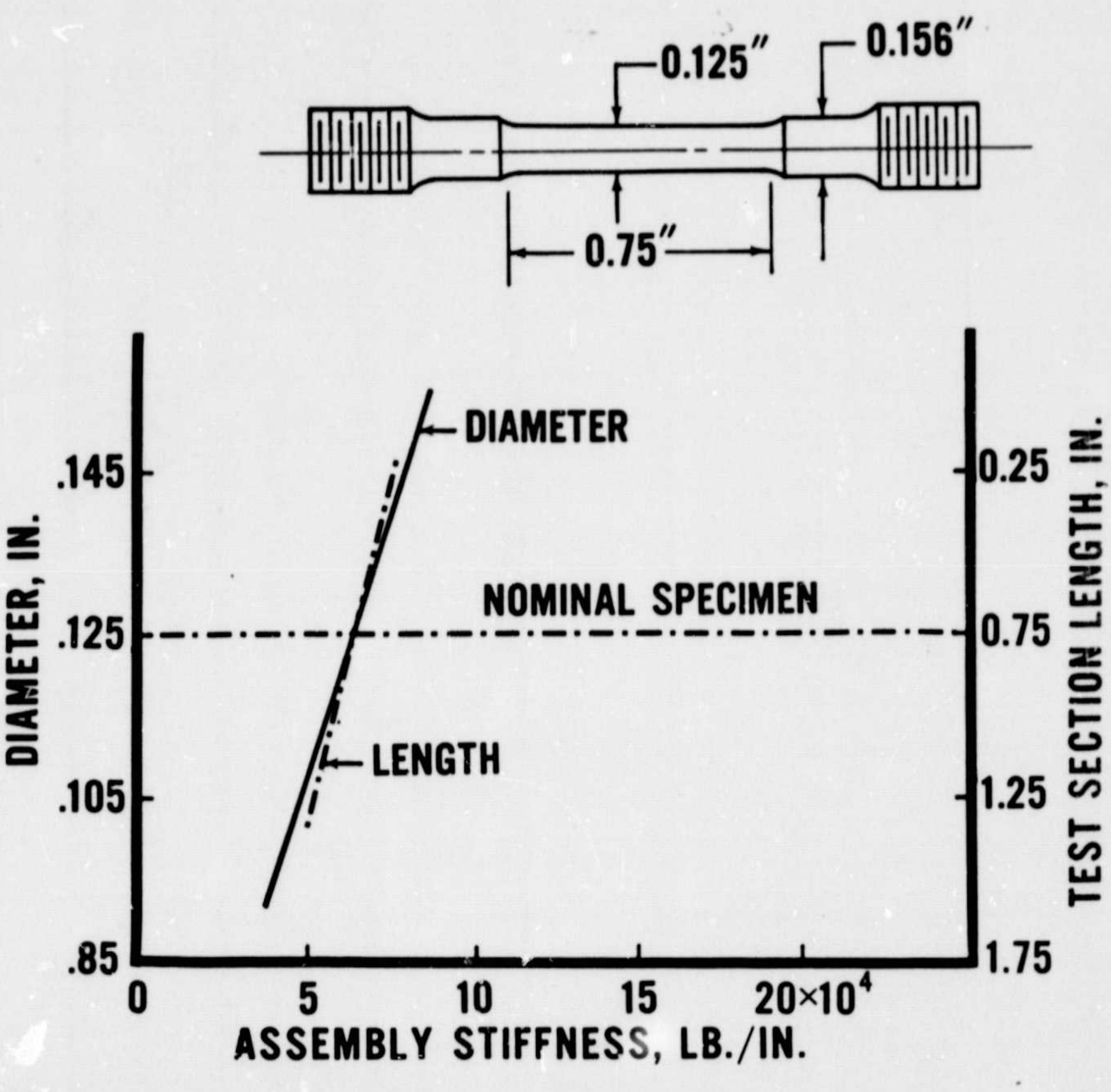
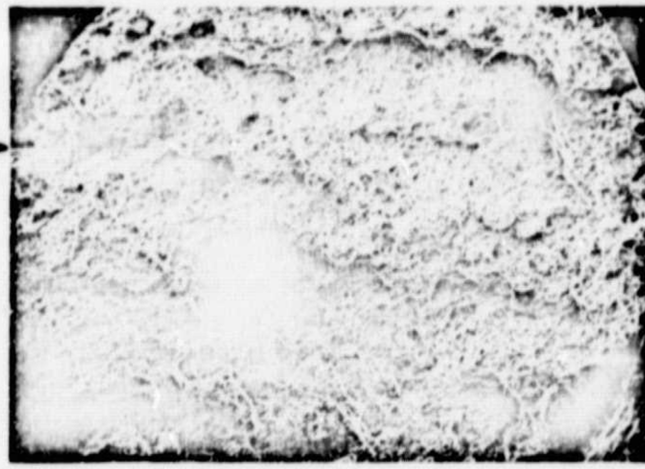


FIGURE 22 EFFECT OF VARYING DIMENSIONS OF 0.125 IN. SPECIMEN ON ASSEMBLY STIFFNESS WITH FRAME A.

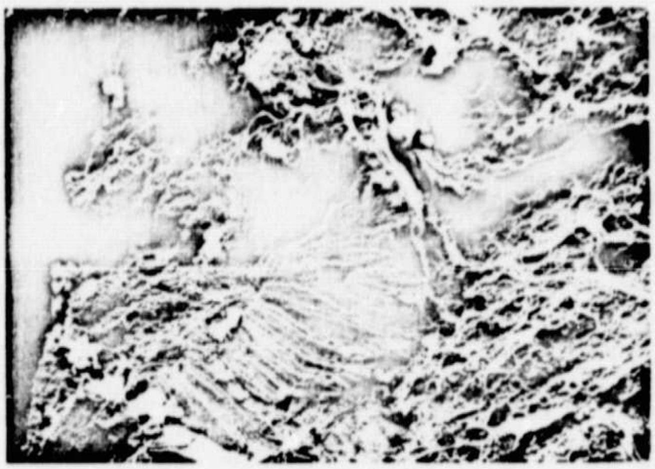
A



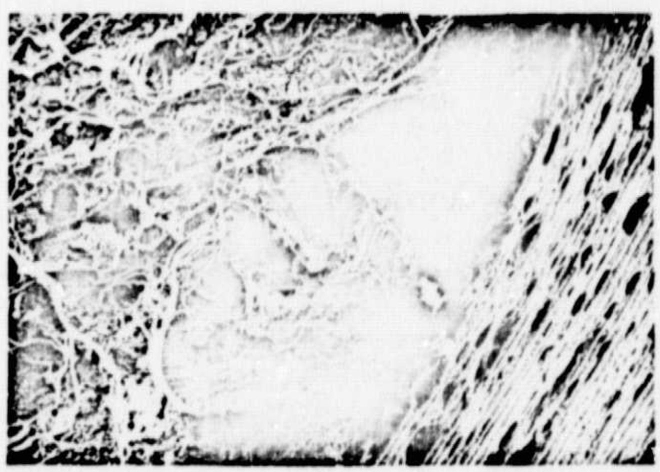
B

MAG: 15 X

A



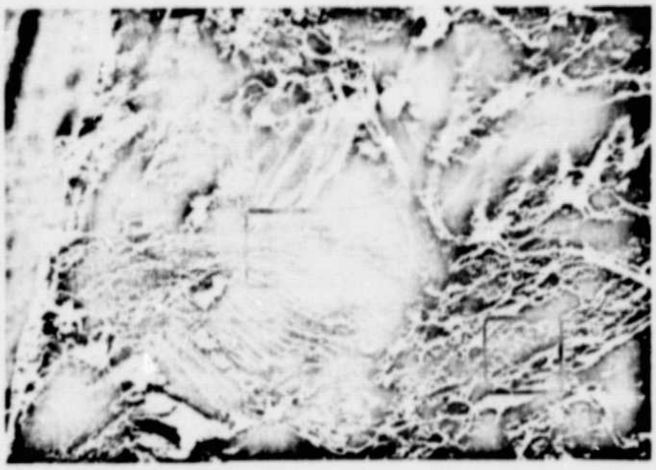
MAG: 100 X



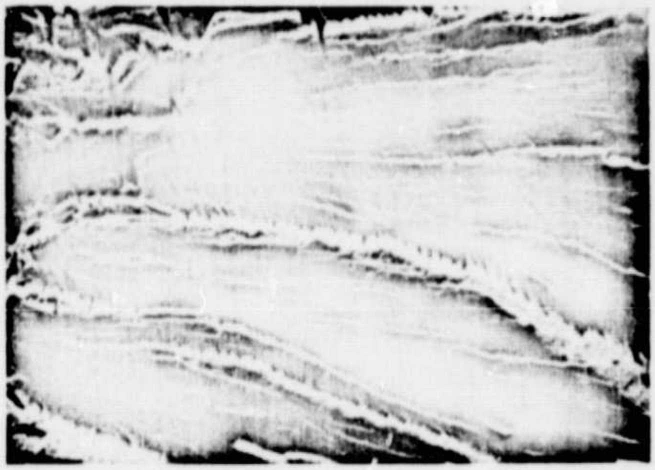
B

MAG: 100 X

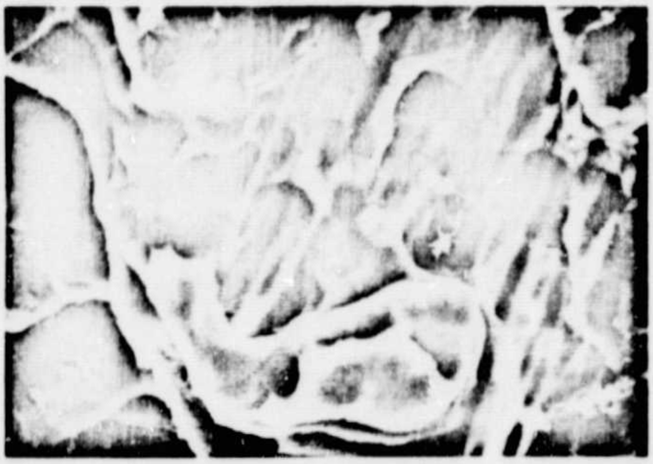
FIGURE 23 - SEM FRACTOGRAPHS OF A 0.250 IN. SPECIMEN OF 7XXX-T7351 ALLOY STRESSED 75% YS THAT FAILED DURING 25 DAYS EXPOSURE TO THE 3.5% NaCl ALTERNATE IMMERSION. SITES A AND B INDICATE CORROSION PITS WITH TRANSGRANULAR CRACKS EXTENDING INTO THE METAL FROM THE BOTTOMS OF THE PITS



TRANSGRANULAR CRACK AT SITE A, FIG. 23 100 X



SURFACE OF TRANSGRANULAR CRACK 1000 X



SURFACE OF TENSION FRACTURE 1000 X

FIGURE 24 - SEM FRACTOGRAPHS CONTRASTING THE CLEVAGE TYPE SURFACE OF THE TRANSGRANULAR CRACK WITH THE DIMPLE RUPTURE SURFACE OF THE TENSION FRACTURE AT THE CENTER OF THE SPECIMEN.

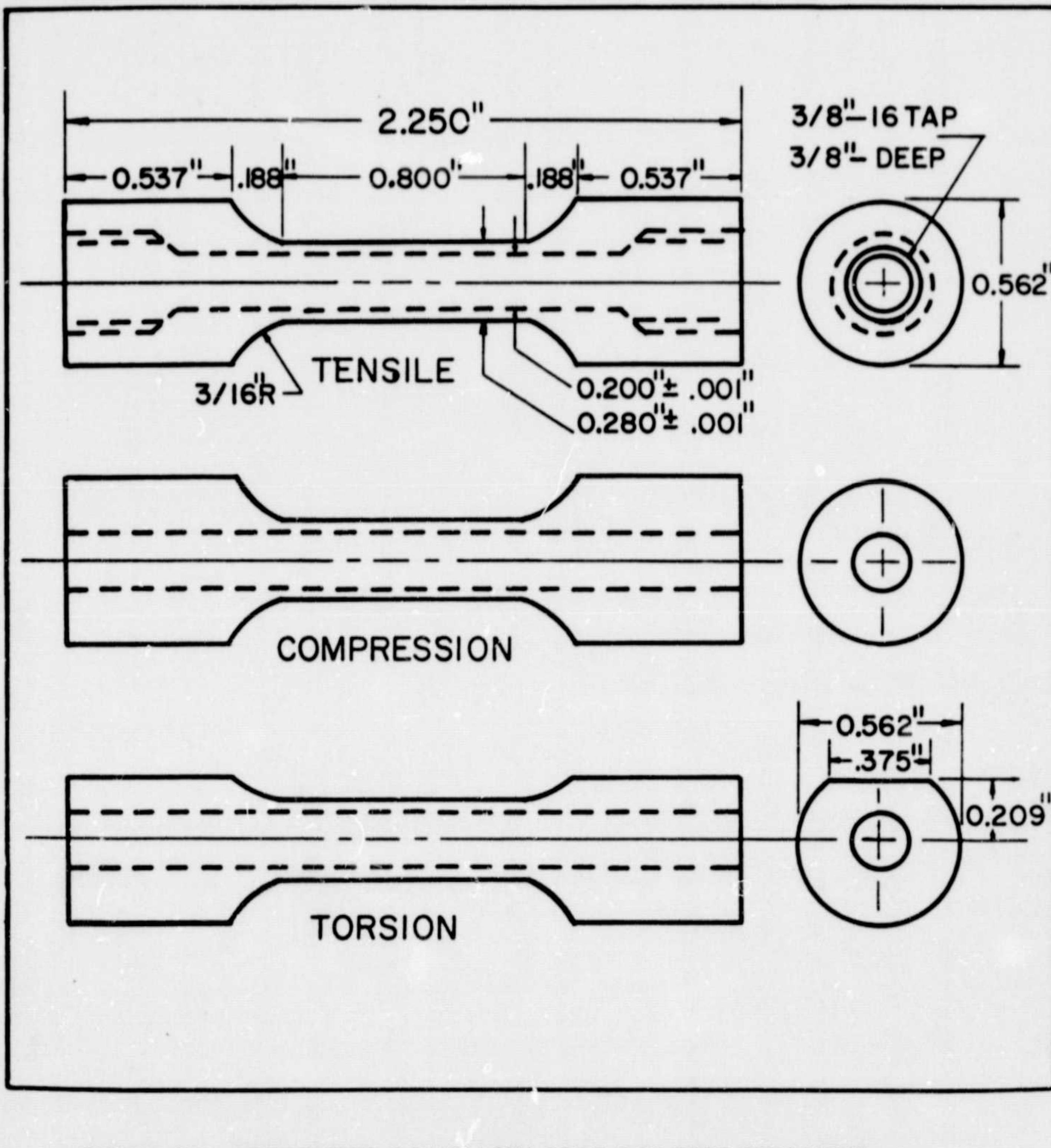


FIGURE 25 - DIMENSIONS OF HOLLOW-CORE SCC TEST SPECIMENS.

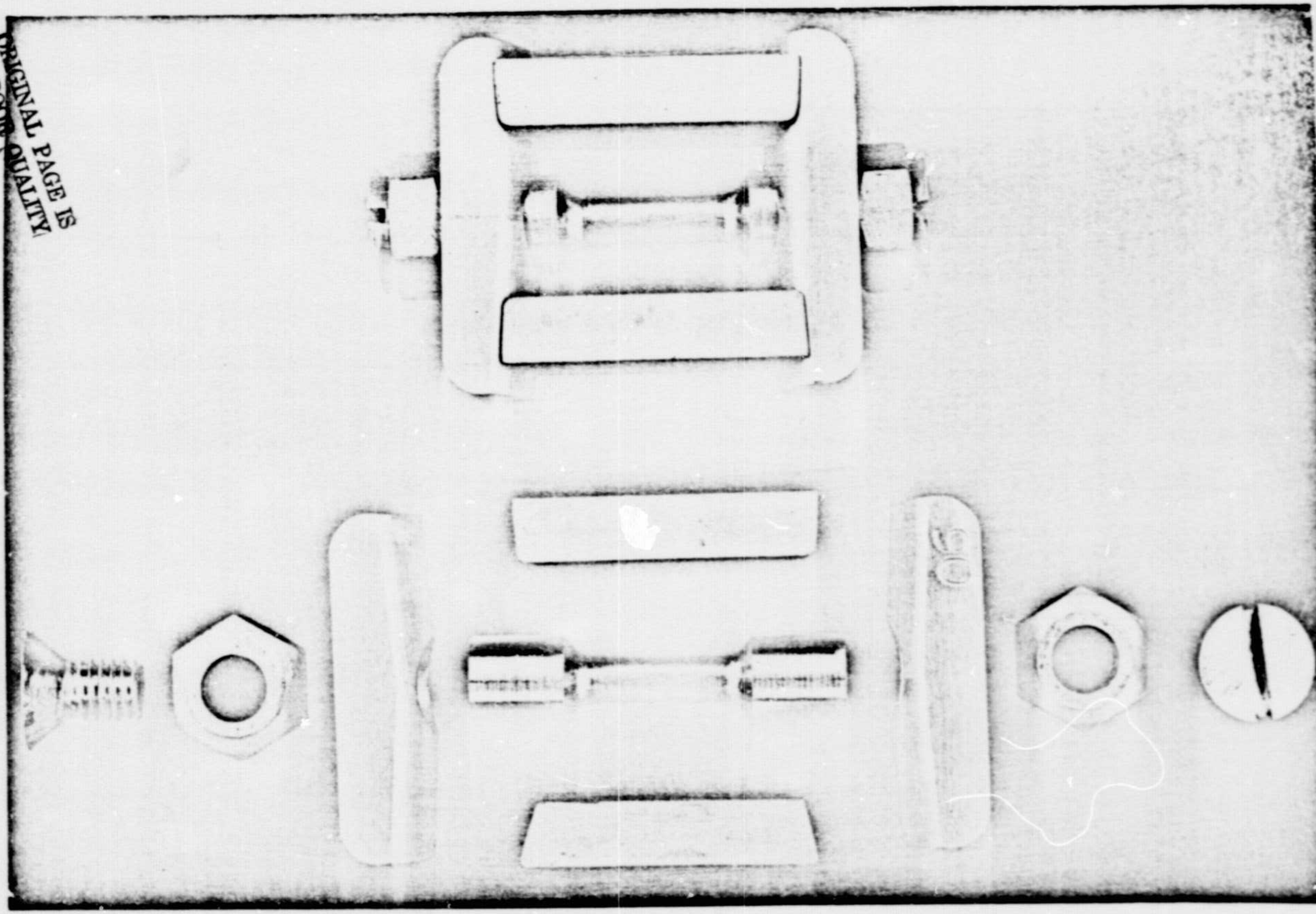


FIGURE 26 - ASSEMBLED AND EXPLODED VIEW OF THE HOLLOW CORE SPECIMEN STRESSED IN TENSION.

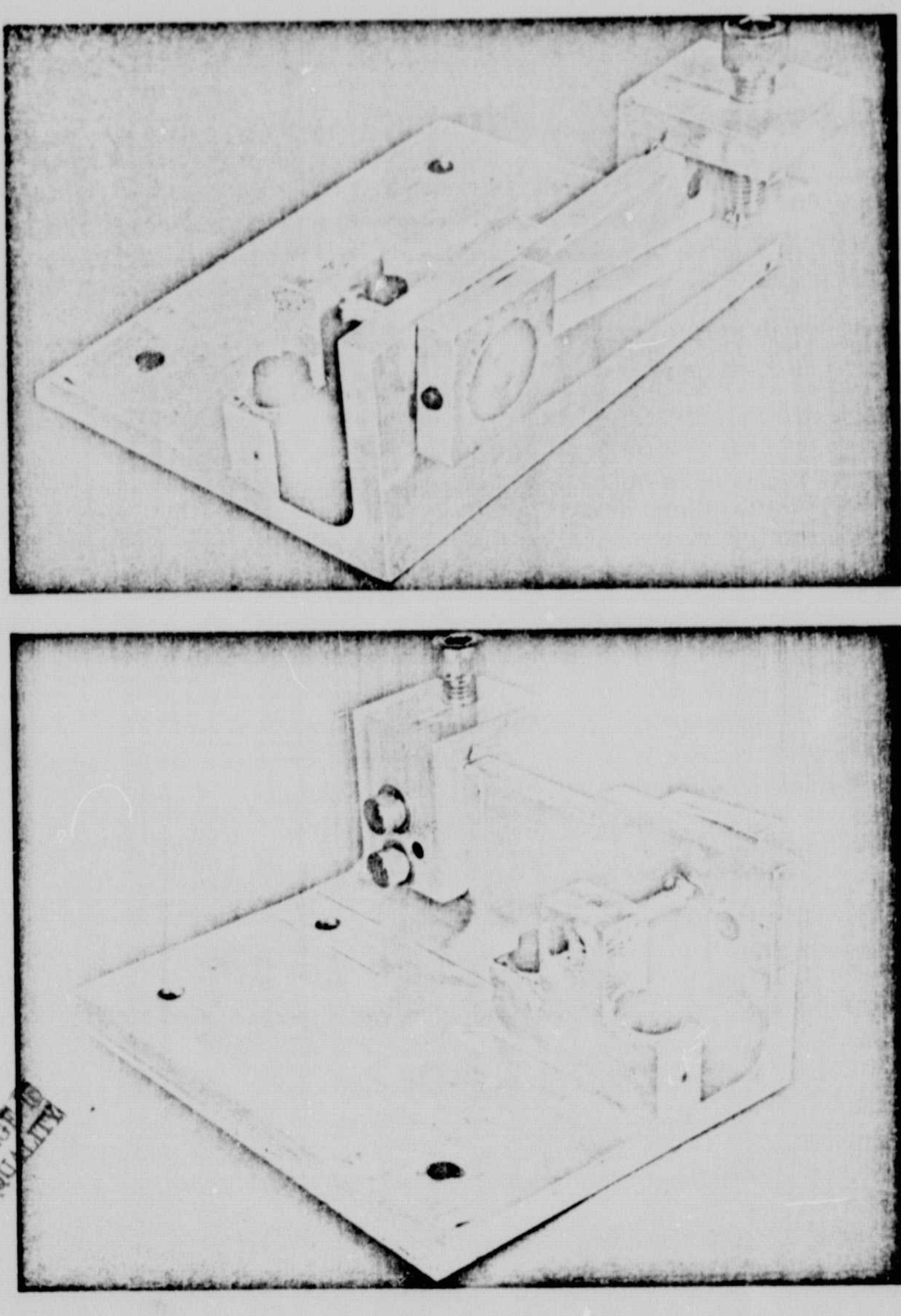


FIGURE 27 - FIXTURE FOR STRESSING HOLLOW CORE SPECIMENS IN TORSION.

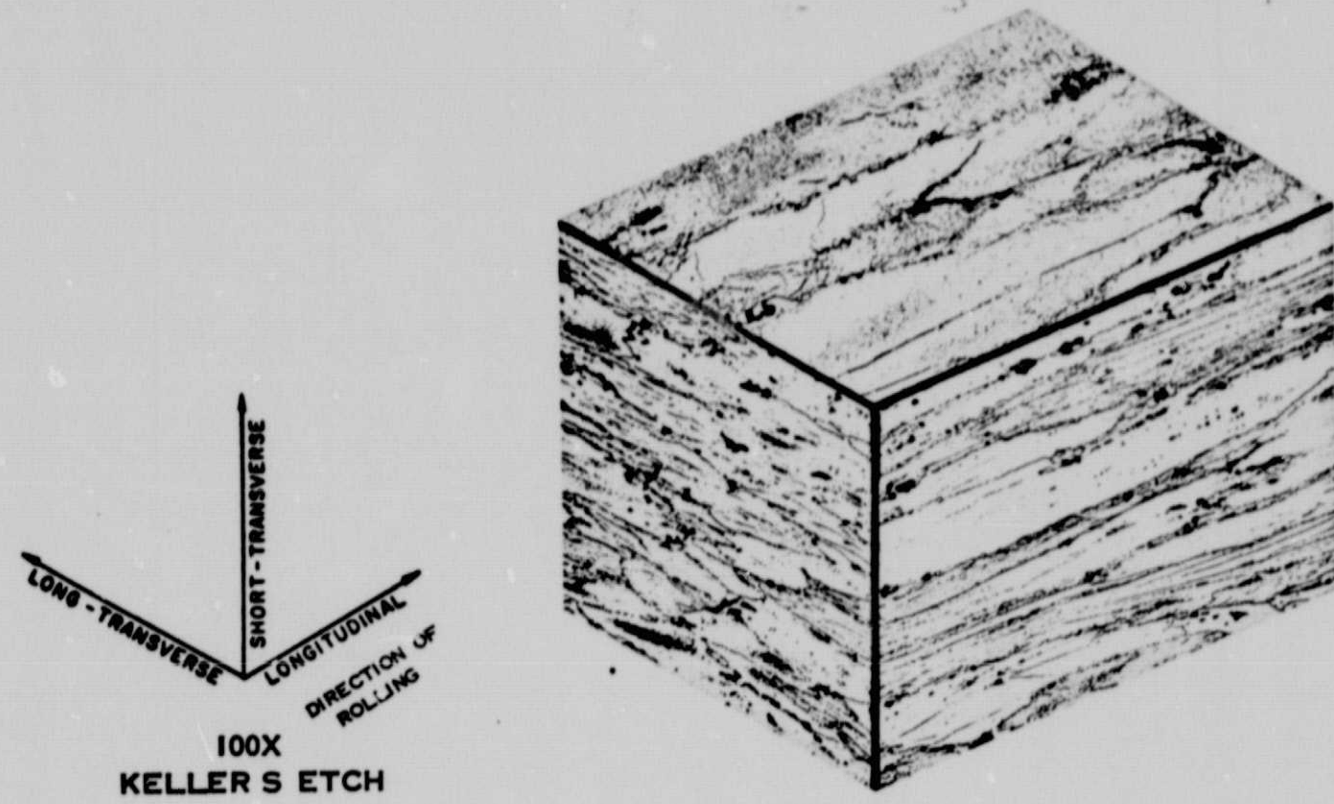
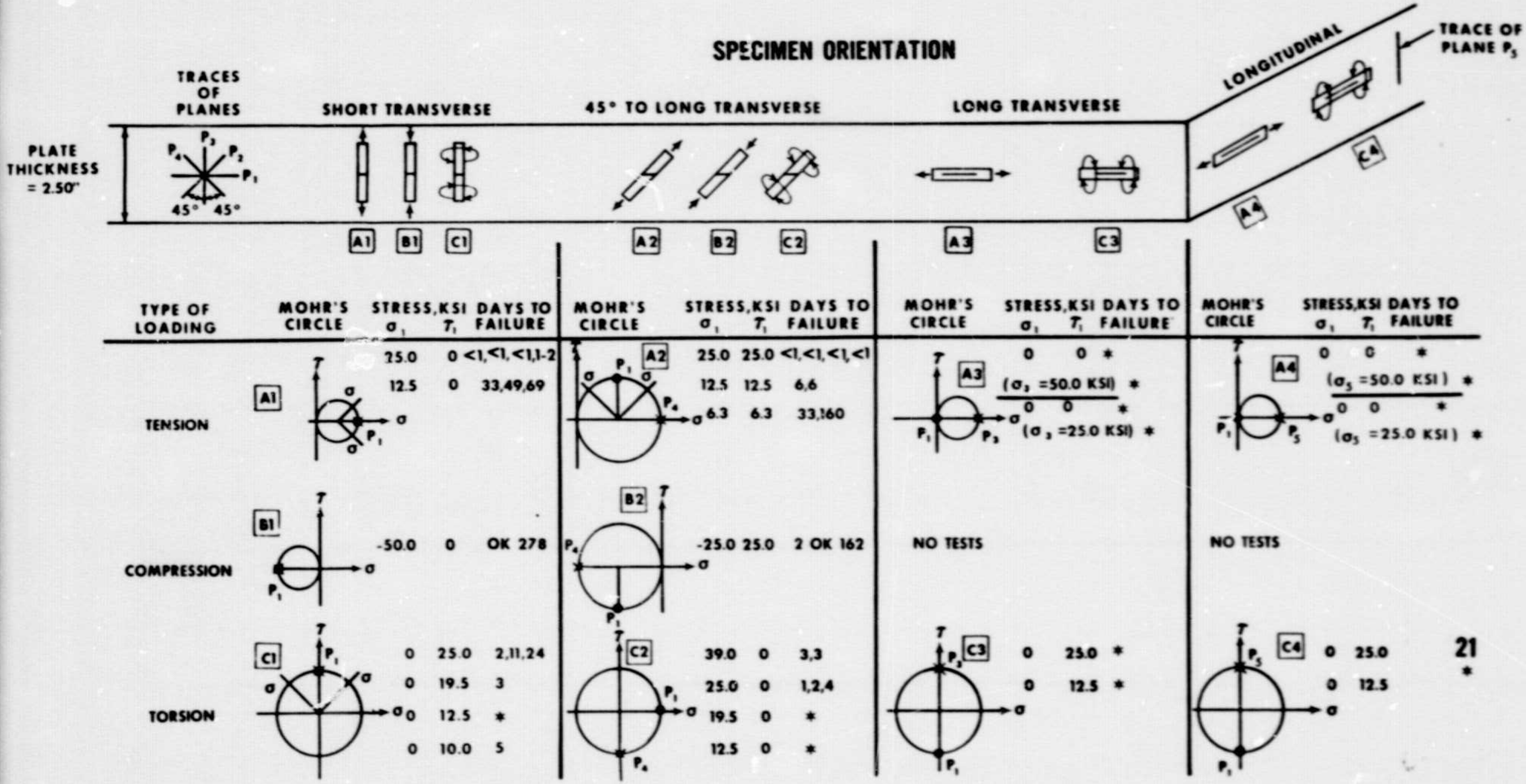


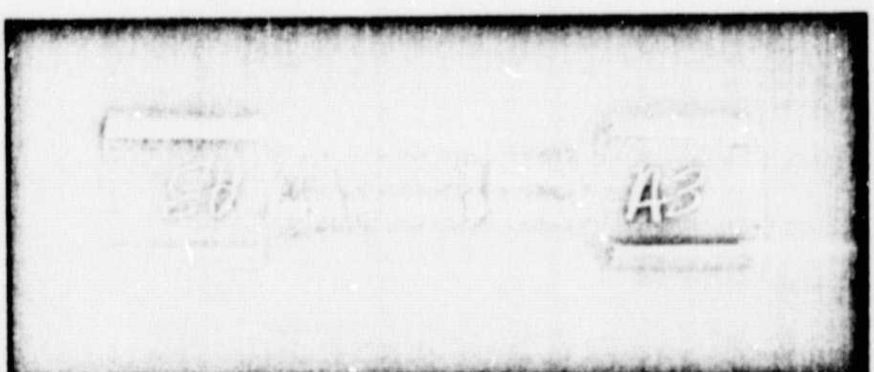
FIGURE 28 - GRAIN STRUCTURE AT MIDPLANE OF 2.500" THICK PLATE OF 7075-T651 ALLOY



NOTES: σ & τ_1 ARE NORMAL AND SHEAR STRESS(KSI) ON PLANE P_2, INDICATED BY (·) ON MOHR'S CIRCLES.
(x) ON MOHR'S CIRCLES INDICATES STRESS ON PLANE NORMAL TO SPECIMEN AXIS.
* INDICATES TESTS TO BE RUN.

FIGURE 29 STRESS-CORROSION TESTS OF HOLLOW 0.280 IN. DIAM. SPECIMENS OF 7075-T651

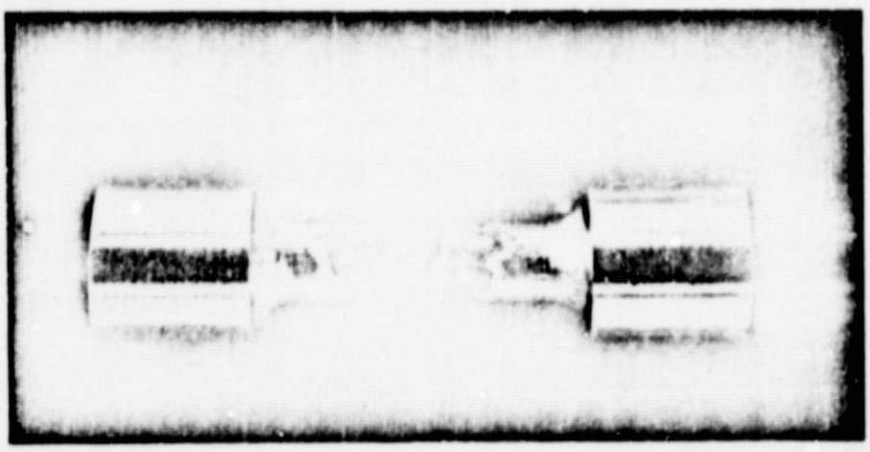
NEG. NO. 182241A **KELLER'S ETCH** **MAG: 100 X**



NEG. NO. 7012053 **MAG: 1.5 X**

FIGURE 30 - 7075-T651 HOLLOW CORE SPECIMEN (S-367115-A3) ORIENTED IN THE SHORT TRANSVERSE DIRECTION THAT FAILED DURING THE THIRD DAY WHEN TORSION LOADED TO A STRESS OF 25 KSI.

NEG. NO. 182311A KELLER'S ETCH MAG: 100 X

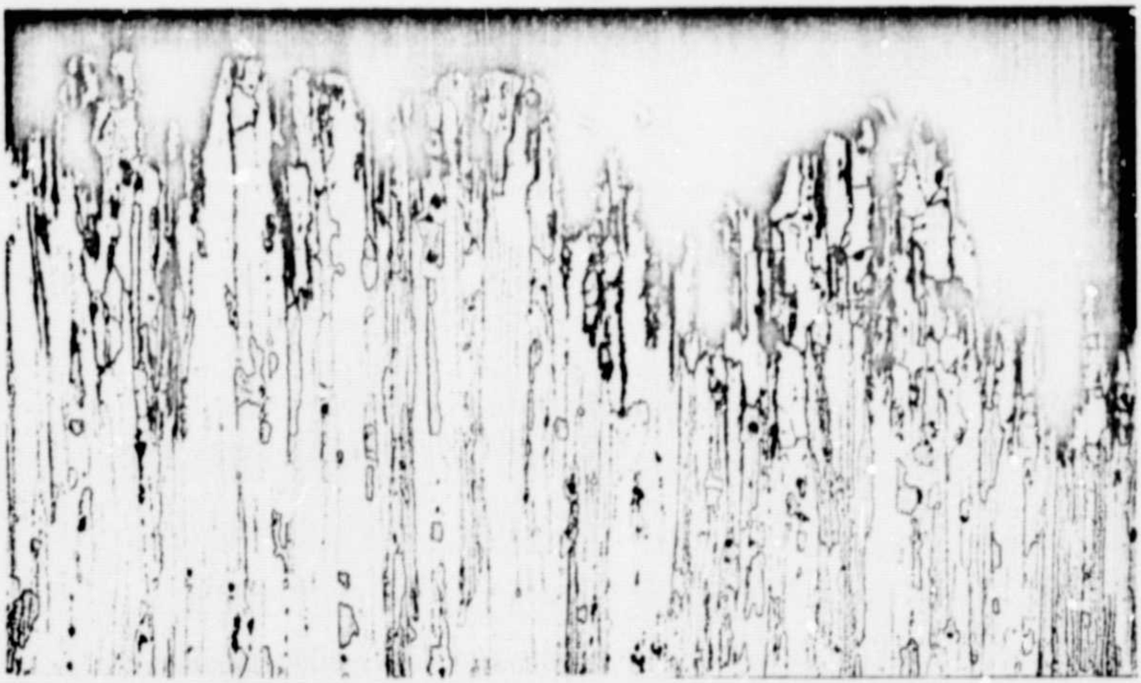


NEG. NO. 7012055 MAG: 1.5 X

FIGURE 31 - 7075-T651 HOLOW CORE SPECIMEN (S-367115-D3) ORIENTED AT 45° TO THE LONG TRANSVERSE DIRECTION THAT FAILED IN LESS THAN 1 DAY WHEN LOADED IN TENSION TO A STRESS OF 50 KSI.

S. NO. 367115-C4 NEG. 185974A KELLER'S ETCH MAG: 100 X

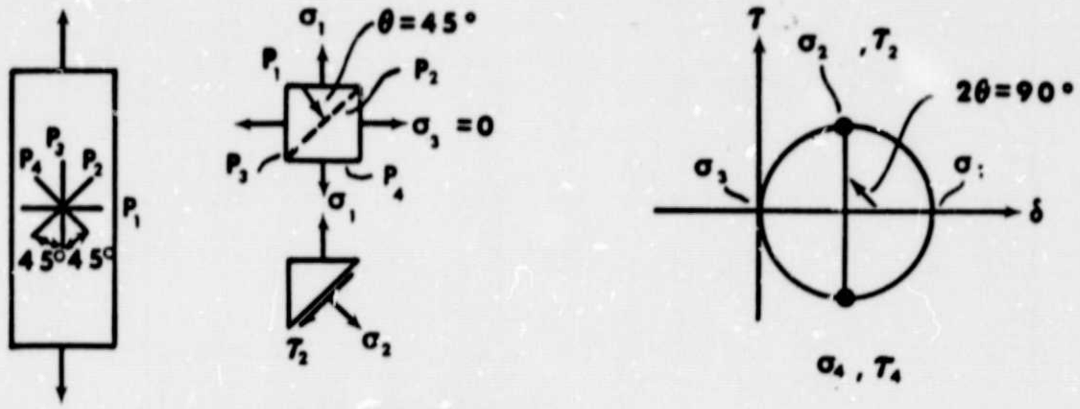
45-DEGREE SPECIMEN (CASE B2) COMPRESSION LOADED TO 25 KSI AND EXPOSED 162 DAYS WITHOUT FAILURE. ARROW DENOTES THE ONLY STRESS-CORROSION CRACK DETECTED.



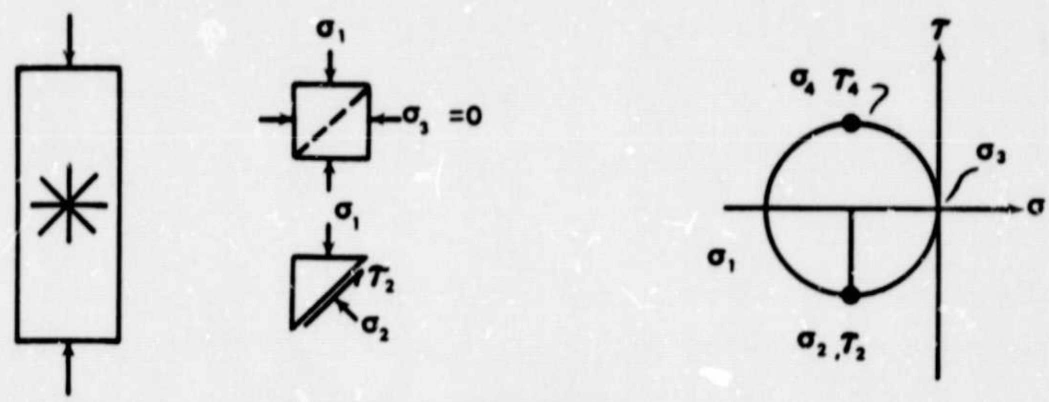
S. NO. 367115-B8 NEG. 185975A KELLER'S ETCH MAG: 100 X

SHORT-TRANSVERSE SPECIMEN (CASE B1) COMPRESSION LOADED TO 50 KSI AND EXPOSED 278 DAYS WITHOUT FAILURE.

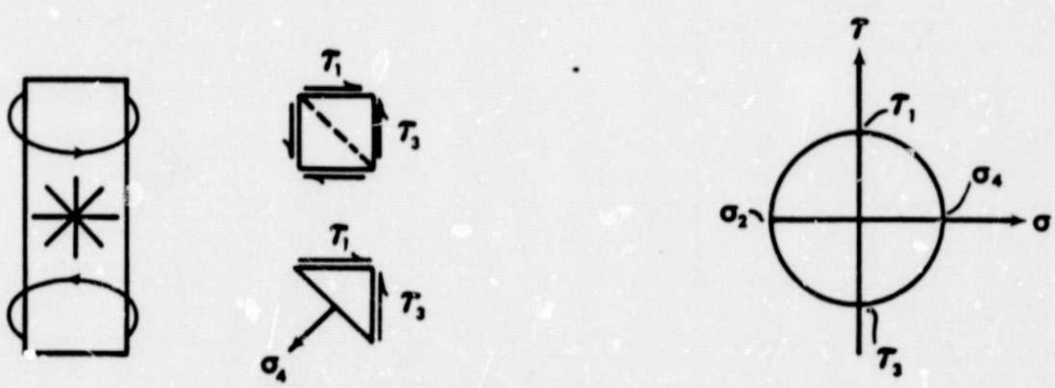
FIGURE 32 - CROSS-SECTIONS THROUGH 7075-T651 HOLLOW CORE SPECIMENS LOADED IN COMPRESSION.



(a) TENSION



(b) COMPRESSION



(c) TORSION

FIG. 33 MOHR'S CIRCLES SHOWING STRESS STATES FOR TENSION, COMPRESSION & TORSION LOADING

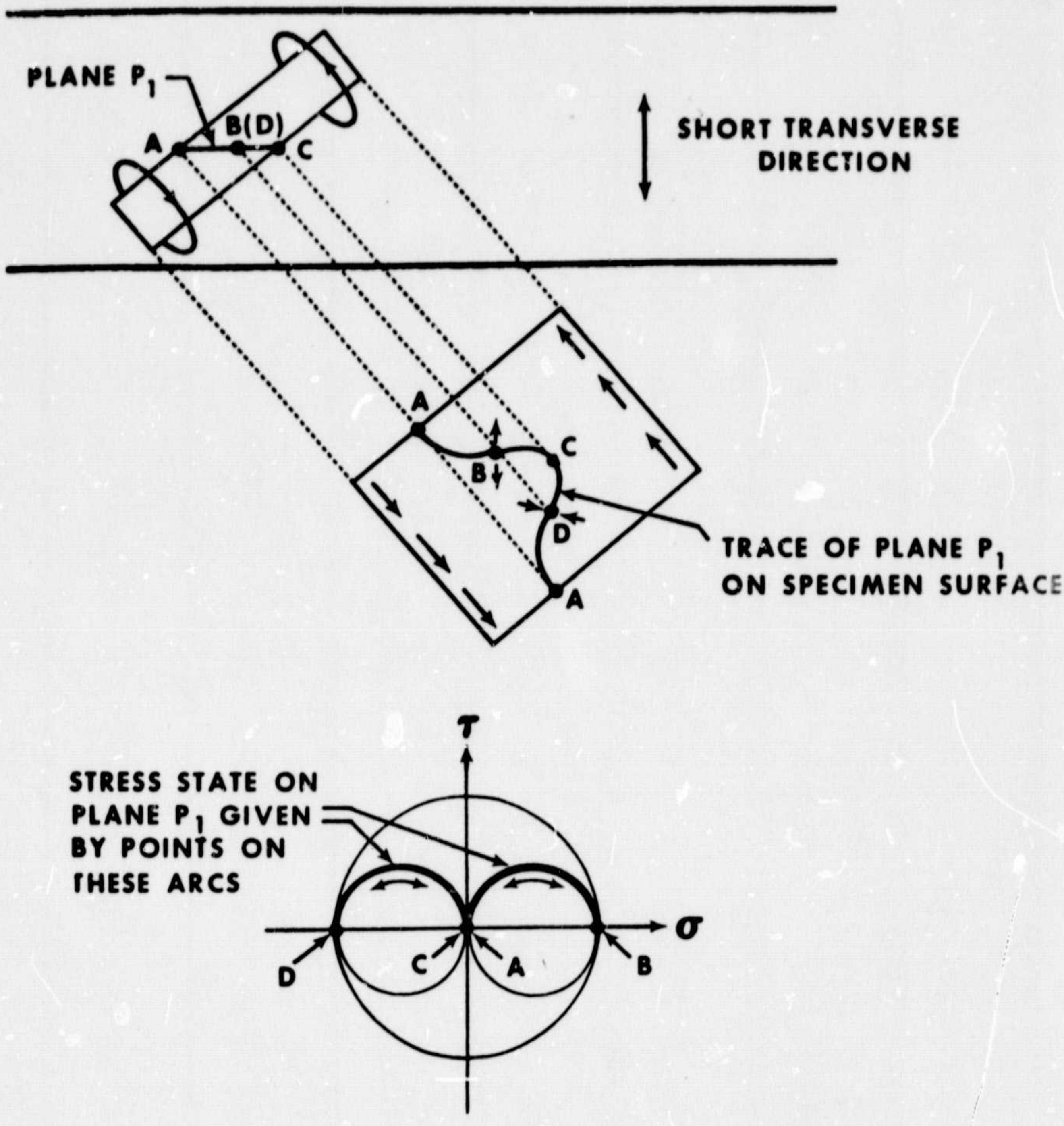


FIGURE 34 STRESS STATE ON SURFACE OF SPECIMEN LOADED IN TORSION AND ORIENTED AT 45° TO PLATE SURFACE

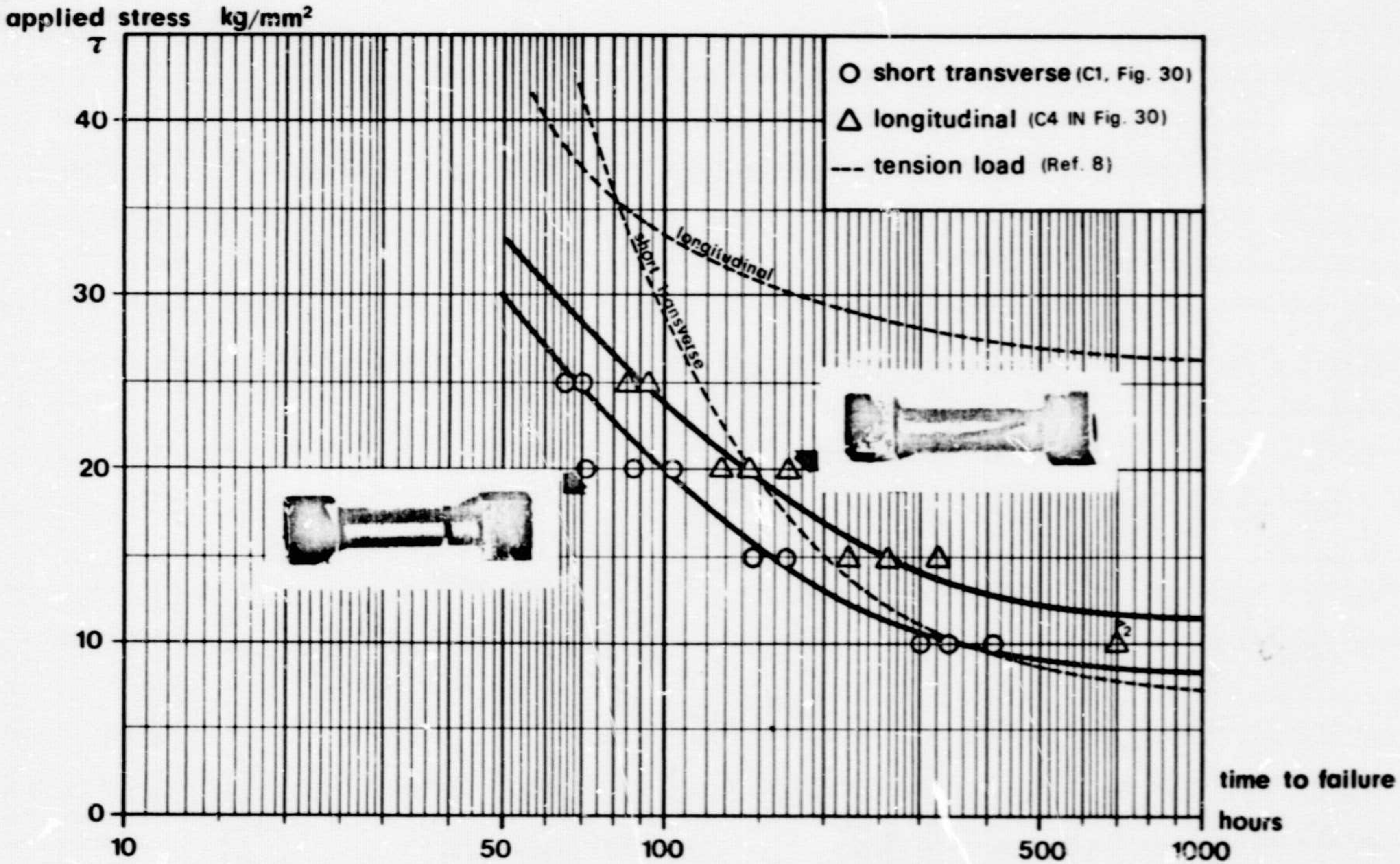


FIGURE 35 - TORSION LOAD SCC TESTS OF 2" THICK PLATE OF 7075-T651 CONTINUOUS IMMERSION IN 3.5% NaCl SOLUTION (BOLLANI (15))

Appendix A

REFERENCES

(1) Sprowls, D. O., Shumaker, M. B., Walsh, J. D., and Coursen J. W., "Evaluation of Stress-Corrosion Cracking Using Fracture Mechanics Techniques", Final Report of Government Contract NAS 8-21487 - Part I for the period of 7/1/69 through 2/29/72.

(2) Mears, R. B., Brown, R. H., and Dix, E. H., Jr., "A Generalized Theory on Stress Corrosion of Alloys", Symposium on Stress-Corrosion Cracking of Metals, 1944, p. 335, published jointly by ASTM and AIME.

(3) Brown, R. H., and Sprowls, D. O., "Electrochemical Aspects of the Mechanism of Stress-Corrosion Cracking", Liberty Bell Corrosion Course II, Sept., 1966.

(4) "Aluminum Standards and Data" - Third Edition 1972-73, published by the Aluminum Association.

(5) Sprowls, D. O., Lifka, B. W., and Shumaker, M. B., "Evaluation of Stress-Corrosion Cracking Susceptibility Using Fracture Mechanics Techniques", Tenth Quarterly Report of Government Contract NAS 8-21487 for the period of 10/1/70 through 12/31/70.

(6) Lifka, B. W., and Sprowls, D. O., "Stress Corrosion Testing of 7079-T6 Aluminum Alloy in Various Environments," ASTM Special Technical Publication No. 425, pp. 342-362, Dec., 1967. Library of Congress Catalog Card Number 67-20038.

(7) Shumaker, M.B., Kelsey, R.A., Sprowls, D.O., and Williamson, J.G., "Evaluation of Various Techniques for Stress Corrosion

Testing Welded Aluminum Alloys", ASTM Special Technical Publication 425, pp. 317-341, Dec., 1967. Library of Congress Catalog Card Number 67-20038.

(8) Sprowls, D. O., and Brown, R. H., "What Every Engineer Should Know About Stress Corrosion of Aluminum", Metals Progress 81, No. 4, pp. 79-85 and 81, No. 5, pp. 77-83, 1962.

(9) Material Specifications applicable to 7075-T73 products, such as: Military Specification MIL-A-22771 for forgings and Federal Specifications QQ-A-200/11 for extruded shapes, QQ-A-225/9 for rolled shapes and QQ-A-250/12 for rolled plate.

(10) Aluminum Association - ASTM Joint Task Group (G01.06.91) for Stress Corrosion Testing 7XXX Aluminum Alloys Containing Copper.

(11) Sprowls, D. O., Lifka, B. W., Vandenburgh, D. G., Horst, R. L., and Shumaker, M. B., "Investigation of the Stress-Corrosion Cracking of High Strength Aluminum Alloys", Final Report of Government Contract NAS 8-5340 for the period May 6, 1963 to October 6, 1966.

(12) Nordmark, G. E., Lifka, B. W., Hunter, M. S., and Kaufman, J. G., "Stress-Corrosion and Corrosion-Fatigue Susceptibility of High Strength Aluminum Alloys", Final Report of Government Contract AF33(615)-67-C-1922 for the period June 1, 1967 to October 31, 1970.

(13) Nielsen, N. A., "Observations and Thoughts on Stress Corrosion Mechanisms", ASTM 1970 Gillett Memorial Lecture, Corrosion, Vol. 27, No. 5 (May, 1971), pp. 173-188.

(14) Seely, F. B. and Smith, J. O., "Advanced Mechanics of Materials", published by John Wiley and Sons, Inc., New York, N.Y., Second Edition, 1952, p. 49.

(15) Bollani, G., "A Contribution to Stress-Corrosion Testing of Aluminum Alloys", Proceedings of AGARD conference No. 98, Oct. 5-6, 1971, AGARD-CP-98, pp. 18.1-18.11.

(16) Craig, H. L., Jr., Sprowls, D. O. and Piper, D. E., Handbook on Corrosion Testing and Evaluation, Edited by W. H. Ailor, John Wiley & Sons, Inc., New York City, 1971, p. 231.

Appendix B

PROCEDURE FOR DETERMINING STRESSES IN NOTCHED SPECIMENS

The change in average net section tensile stress due to cracking, as simulated by sharp V-notches, was determined as follows:

The relationship between load and fixture deflection was experimentally determined as indicated in Figure B1(a). Load deflection data were then obtained for the test section of specimens notched at their midlength to give nominal reductions in area of 0, 20, 40, 60 and 80 per cent, as shown in Figures B1(b). If P_S^o is the force required to stress a plain specimen to the initial stress σ^o and P_S' the force on the specimen for a given crack depth, then to satisfy equilibrium requirements:

$$P^o_S = P^o_F$$

$$P'_S = P'_F$$

Let ΔL^o_S be the initial change in specimen length produced by P_S^o and $\Delta L'_S$ the change in length corresponding to P_S'. The incremental change in specimen length, $d\,(\Delta L)_S$, can be found from the specimen load-deflection data, as shown in Figure B1(b). To satisfy compatibility, the incremental change in specimen test section must equal the incremental deformation of the stressing assembly, or

$$d\,(\Delta L)_S = d\,(\Delta L)_F$$

where $$d\,(\Delta L)_F = \Delta L^o_F - \Delta L'_F$$

From the value of P'_S which satisfies the above requirements the average net section stress is:

$$\sigma' = \frac{P'_S}{A'}$$

where A' is the net area for the given crack depth.

Net section stresses were calculated using a computer program in which compliance data were represented by appropriate equations and P'_S determined by iteration.

The above procedure was used with specimens obtained from the eight aluminum alloy plates listed in Table B-I.

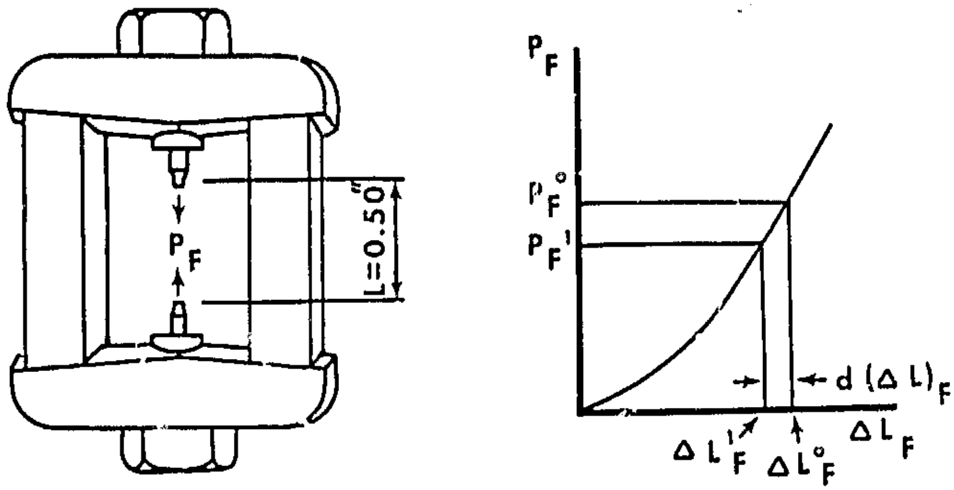
TABLE B-I

TENSILE PROPERTIES AND CHEMICAL COMPOSITIONS OF PLATES USED IN COMPLIANCE TESTS

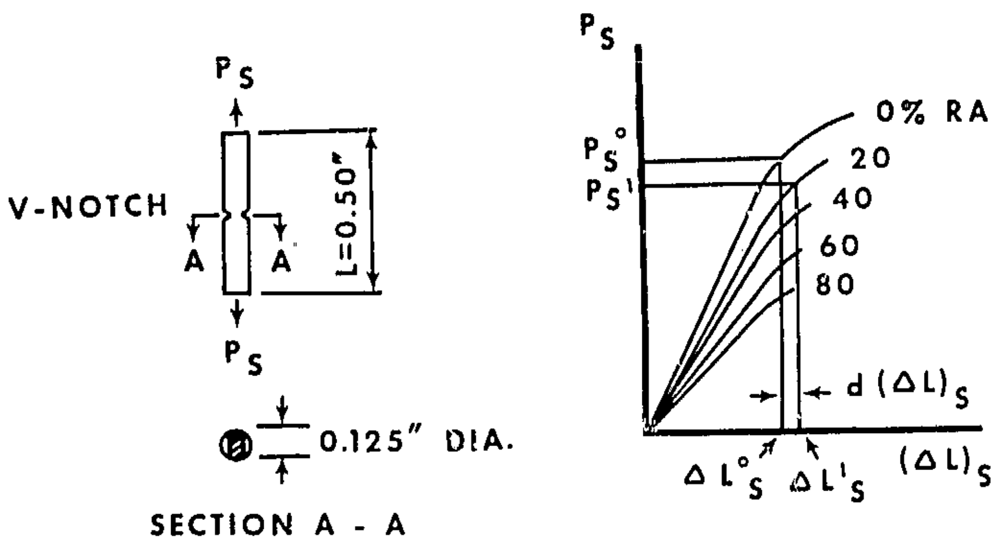
Alloy	S. No.	Thick. In.	Test Direction	TS ksi	YS ksi	El %
6061-T651	314729	1/2	Long.	45.1	42.6	20.1
2219-T37	323038	2-1/2	S.T.	55.3	40.7	8.9
5083-H131	344649	2	S.T.	47.2	35.7	8.0
7039-T63	295505	2	S.T.	63.2	54.3	5.8
7075-T651	322720	2-1/2	S.T.	74.2	66.5	1.2
7075-T7351	322721	2-1/2	S.T.	66.7	57.8	3.4
7079-T651	248667	2	S.T.	76.8	66.3	3.2
7178-T651	323080	2	S.T.	79.5	70.8	1.0

Alloy	Chemical Composition - Per Cent										
	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	Be	Zr	V
2219-T37	0.12	0.22	6.22	0.25	0.01	0.07	0.00	0.08	----	0.13	0.09
5083-H131	0.11	0.16	0.03	0.81	4.46	0.02	0.08	0.02	----	----	----
6061-T651*	0.6	----	0.25	----	1.00	----	0.20	----	----	----	----
7039-T63*	----	----	----	0.27	2.80	4.00	0.20	----	----	----	----
7075-T651	0.11	0.20	1.75	0.04	2.44	5.71	0.20	0.03	0.002	----	----
7075-T7351	0.12	0.21	1.81	0.04	2.52	5.90	0.20	0.03	0.002	----	----
7079-T651	0.10	0.20	0.78	0.22	3.42	4.61	0.19	0.05	0.001	----	----
7178-T651	0.11	0.25	1.75	0.04	2.46	6.67	0.19	0.03	0.002	----	----

* Nominal composition - actual analysis not determined



(A) SPECIMEN - FRAME ASSEMBLY COMPLIANCE



(B) COMPLIANCE OF TEST SECTION OF NOTCHED SPECIMENS

FIGURE B1

PROCEDURE FOR DETERMINING STRESSES IN NOTCHED SPECIMENS